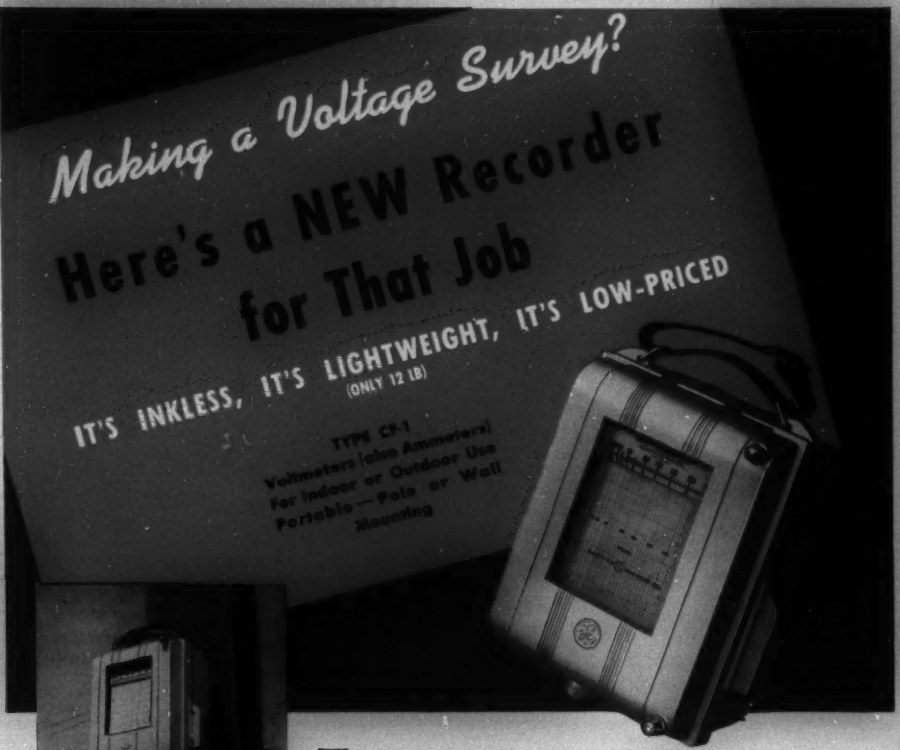
Electrical Engineering

October 1939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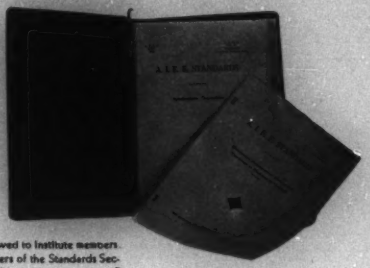
THE Standards of the American Institute of Electrical Engineers now comprise forty-eight sections on electrical machinery and apparatus. They are chiefly devoted to defining terms, conditions, and limits which characterize behavior, with special reference to acceptance tests, and many of them are recognized officially as American Standards.



The Standards available are listed below, together with prices. A discount of 50% is allowed to Institute members. Such discount is not applicable on extra copies unless ordered for other members. Numbers of the Standards Sections should be given when ordering. A binder (illustrated above) for standards is available. Long wearing stiff covers, resembling leather, lettered in gold. Price $1.75 net.

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Six such sections are now available in report form for purpose of criticism, and copies will be sent without charge upon request. These sections are as follows:

No. 6	Mercury Arc Rectifiers.	40	Electrical Recording Instruments.
25	Fuses Above 600 Volts.	—	Test Code for Transformers.
501	Test Code for D-C Machines.	—	Test Code for Synchronous Machines.

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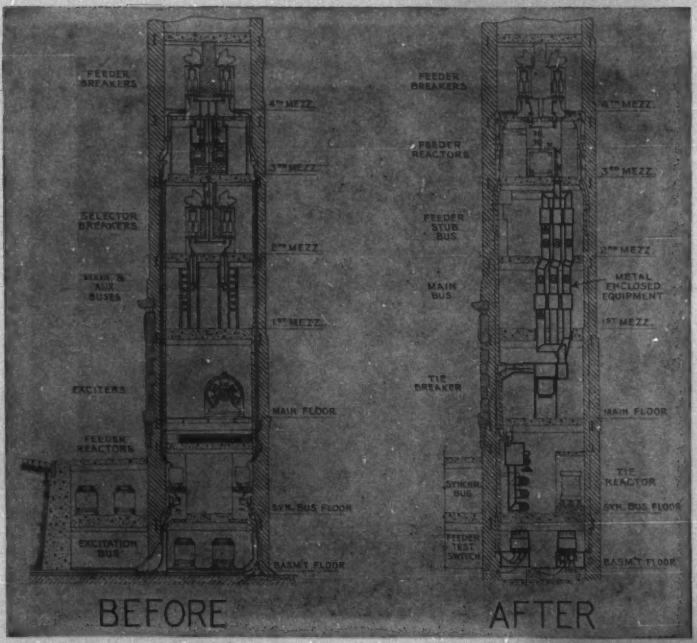
—BEFORE AND AFTER



These sketches show a typical and authentic case of modernization of a switchhouse structure of a large metropolitan electric power system. They were drawn with Typhonite Eldorado, The Master Drawing Pencil, using degrees H, 2H, 9H, F and HB. The sketches show what has been and can be done in adapting existing structures toward the ever more stringent operating requirements of such metropolitan systems.

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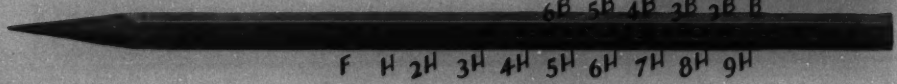

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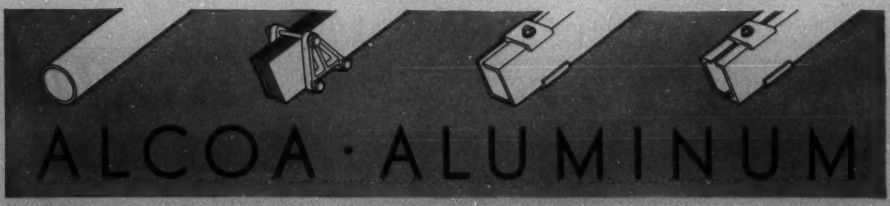
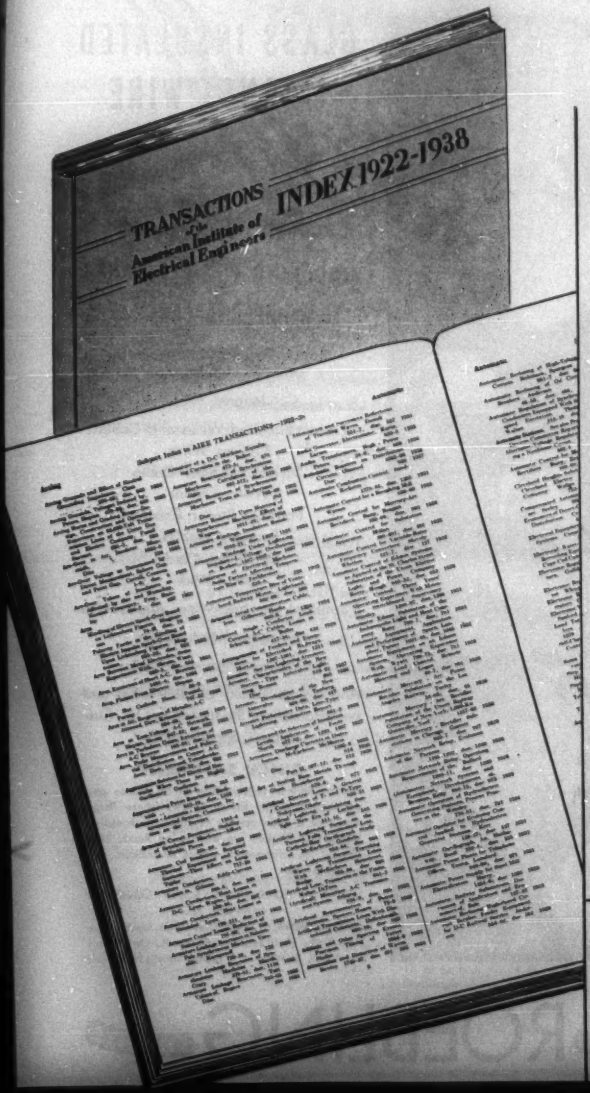


NEW INDEX

of the AIEE TRANSACTIONS from 1922 to 1938 Inclusive



•A new cumulative Index, covering the papers and discussions published in the AIEE TRANSACTIONS from January 1, 1922 to December 31, 1938, is now available for distribution. This new compilation constitutes the fourth in a series of published volumes of indexes to the technical papers and related discussions that have been published by the Institute since 1884.

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1. Subject Index. Arranged alphabetically, the more than 9,000 entries in this section provide multiple references to every technical paper and related discussion published during the 17 years covered by the Index. The title of each technical paper has been entered under every significant word in the title and has been given certain additional listings such as the subject name of the technical committee responsible for the review and recommendation of the paper. Thus, a searcher may effectively approach a desired reference through any of several key words associated with the subject matter of the item sought.

2. Author Index. Every author or co-author of a technical paper or discussion published in the TRANSACTIONS during the 17 years covered by the Index is listed alphabetically in this section. The 11,000-odd entries give direct page reference to each paper and each published discussion.

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Electrical Engineering

Registered U. S. Patent Office

for October 1939—

The Cover: New Union Pacific steam-electric locomotive; see pages 407–13. General Electric Photo

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VOLUME 58 NUMBER 10

Published Monthly by the

American Institute of Electrical Engineers

(Founded 1884)

F. MALCOLM FARMER, President H. H. HENLINE, National Secretary

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Entered as second class matter at the Post Office, Easton, Pa., April 20, 1932, under the Act of Congress March 3, 1879. Accepted for mailing at special postage rates provided for in Section 1103, Act of October 3, 1917, authorized on August 3, 1918. ¶ Publication Office: 20th & Northampton Streets, Easton, Pa. Editorial and Advertising Offices at the headquarters of the Institute, 33 West 39th Street, New York

¶ Statements and opinions given in articles and papers appearing in "Electrical Engineering" are the expressions of contributors, for which the Institute assumes no responsibility.

¶ Correspondence is invited on all controversial matters.

High Lights

Cable Ratings. The most efficient use of impregnated-paper-insulated lead-covered cable may require occasional emergency loads in excess of ratings specified in standards. Possible shorter cable life and higher losses must be balanced against the cost of larger conductors; cable life depends on the limitations of the insulation and of the sheath, and the heating characteristics of the conduit. One system has established emergency load ratings for cables operating from 120 to 132,000 volts (*Transactions pages 535–56*). A study of the effect of intermittent operation of paper-insulated 15-kv cables at temperatures above the level generally accepted as maximum for their class indicates that modern types of cable that permit expansion and contraction of the cable compound without unduly stressing the lead sheath could be operated repeatedly to copper temperatures as high as 100 degrees centigrade (*Transactions pages 556–62*).

Engineering and Social Problems. Because engineering achievements have resulted in so many contributions to society, many believe that engineering methods can be applied equally successfully to social problems. In an article discussing this general subject, the engineer is urged to do what he can to educate and warn the lay public that principles applicable to his inanimate problems cannot be applied directly in the realm of social phenomena (*pages 423–6*).

Transactions Supplement. A special supplement, containing 28 technical papers which will be included in the 1939 annual volume of AIEE TRANSACTIONS but which have not been preprinted in the monthly TRANSACTIONS sections of ELECTRICAL ENGINEERING, will be published in December. Abstracts of the papers included in the supplement appear in this issue (*pages 432–5*).

Traveling-Wave Demonstrator. A device has been built by means of which various types of surges on power transmission lines readily may be visualized. Not only does it aid in gaining an understanding of the nature of these phenomena, but from the results obtained with it important fundamental theoretical relations may be deduced (*pages 414–20*).

Steam-Electric Locomotive. The railroads' newest aid toward faster schedules is the 5,000-horsepower steam-electric locomotive recently placed in service on the Union Pacific System. Each of the two 2,500-horsepower units consists of an electric locomotive with its own high-pressure condensing steam-electric generating plant on board (*pages 407–13*).

Motor Rating. A revised method of rating single-phase motors for compressors for refrigerating machines has been suggested, in order to specify more clearly the motor characteristics for applications where torque rather than temperature is the important consideration (*Transactions pages 519–27*).

Transformer Loading. A method of loading a transformer according to copper temperature as determined by a thermostatic relay utilizes the latent overload capacity of the transformer to permit it to supply overloads until its maximum safe temperature is reached (*Transactions pages 504–14*).

Ratings. Technical, economic, and psychological aspects are involved in the methods of rating electrical machinery and apparatus. Better agreement of existing standards with present-day conditions could be obtained by some modifications (*Transactions pages 499–503*).

New Commitee Chairmen. New chairmen for 1939–40 were appointed for 16 of the Institute's committees, and began their duties August 1. Biographies of a majority of the new chairmen will be found in the Personal Items section of this issue (*pages 443–5*); others in subsequent issues.

Voltage-Regulation Computations. Determination of voltage regulation for four-winding transformers, with load on three windings and the fourth acting as a source, may be simplified by the use of constants obtained directly from the usual two-terminal impedances (*pages 420–1*).

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Temperature Effects. One factor limiting the output of electrical rotating machinery is the rise in temperature that can be tolerated without damage to the machine from distortion of parts and melting of soldered connections (*Transactions pages 514–18*).

Section Activities. Abstract of the report on activities of local AIEE Sections, presented by Chairman H. H. Race at the 1939 summer convention, is published in this issue, with a chart showing results of the Sections committee's survey (*pages 436–7*).

Electricity as a Fire Hazard. Statistics accumulated by one insurance organization show that electricity rates as a strong first contender as fire hazard in industrial plants, with one out of every five industrial fires of electrical origin (*page 427*).

Voltage for Airplanes. Calculations show that for a wide variety of airplanes of different types the voltage for the electrical systems may advantageously be standardized at 24 volts (*pages 428–31*).

Why So Few Famous Engineers Today? This question is asked by a well-known engineer who has summarized some of the answers that have been suggested to him (*page 422*).

Welder Control. Precision control of resistance spot welders is offered by a simplified unit consisting of a synchronous magnetic contactor and a motor-driven timer (*Transactions pages 528–34*).

Coming Soon. Among special articles and technical papers now undergoing preparation for early publication are: an article on vertical-shaft generators, discussing some of their problems and methods of solution, by H. R. Sills (M'31); an article on lightning strokes in field and laboratory, by P. L. Bellaschi (M'34); a paper on induced current in parallel circuits and its effect upon relays by E. H. Bancker (M'30); a paper describing an amplifier-wattmeter combination for the direct measurement of watts and vars by G. S. Brown (A'33) and E. F. Cahoon (A'34); a paper on high-speed-relaying experience and practice by the relay subcommittee of the AIEE committee on protective devices; a paper on emergency ratings by A. H. Kidder (A'29); a paper on the factors affecting are extinction on a Petersen-coil system by J. R. Eaton (M'35); and a paper describing operating experience with Petersen coils on the 66-kv system of the Metropolitan Edison Company in Pennsylvania by H. M. Rankin (M'22) and R. E. Neidig (A'38).

Subscriptions—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii, Philippine Islands, Central and South America, Haiti, Spain, Spanish Colonies; $13 to Canada; $14 elsewhere. Single copy $1.50. ¶ Address changes must be received by the fifteenth of the month to be effective with the succeeding issue. Copies undelivered because of incorrect address cannot be replaced without charge. ¶ ELECTRICAL ENGINEERING is indexed annually by the Institute, weekly and monthly by *Engineering Index*, and monthly by *Industrial Arts Index*; abstracted monthly by *Science Abstracts* (London).

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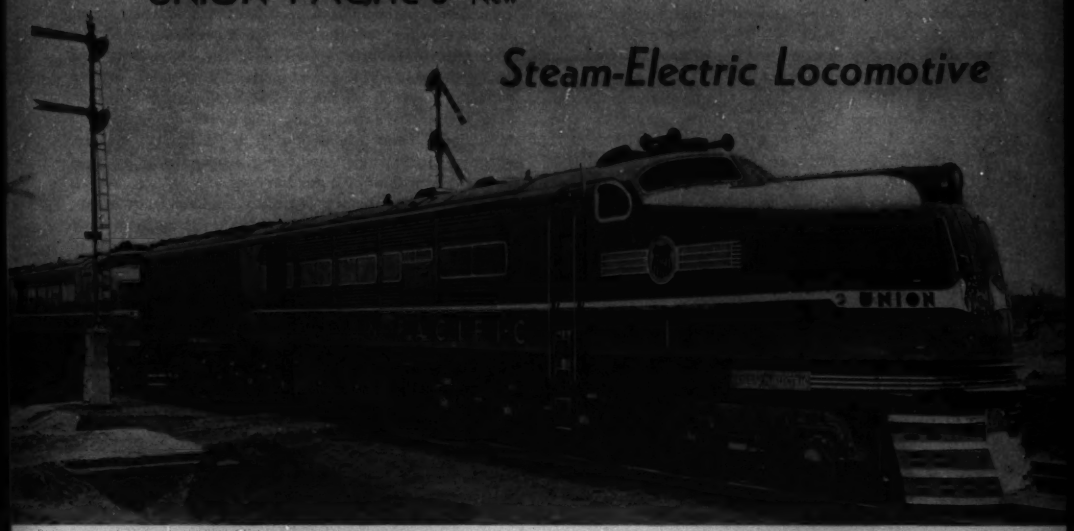
Number of copies this issue 21,100

UNION PACIFIC'S New Steam-Electric Locomotive



The need for faster railroad schedules has necessitated the development of new motive-power units capable of sustained high-speed operation. Newest entrant in that realm is the steam-electric locomotive recently placed in operation by the Union Pacific Railroad.

RAILROAD transportation has been one of the most important factors in the development of the United States and in welding together all its parts into a single nation. All sections of the country have been made accessible by the railroads, and transportation costs have been such that the people of all parts have been able to keep in continuous contact with each other. In recent years, however, automobiles, airplanes, and other new forms of transportation have presented new problems to the railroads. Solution to those problems has been the development of high-speed light-weight rolling stock, which has enabled the railroads to establish faster schedules without the necessity of making expensive alterations in track construction.

About 1932, a special investigation and study was made by the Union Pacific Railroad to determine what could be done to keep its passenger transportation abreast of the times. The results of these studies indicated a need for a radically different type of passenger equipment. At that time, fast steam passenger trains required three nights and two days to run from Chicago, Ill., to the Pacific Coast points of Los Angeles and San Francisco, Calif., and Portland, Ore. It was considered desirable to reduce this time to two nights and one day, but it was not considered possible to accomplish this with the standard steam locomotives then available. After much study and experimenting, it was decided to build a light-weight train consisting of an oil-electric locomotive and new light-weight passenger cars. To reduce wind resistance at high speeds, the train was streamlined.

Before the first oil-electric train was completed, which included three passenger cars and was powered by a 600-horsepower engine, construction on a 6-car Diesel-electric train was started. Since then larger and more powerful Diesel-electric trains have been built and placed in operation, not only on the Union Pacific but on many other roads, providing these roads with a new tool to meet the competition offered by the newer forms of transportation. The latest train of this type consists of 17 cars and is propelled by a three-unit 5,400-horsepower locomotive.

With the use of the Diesel-electric locomotive, it is possible to use one locomotive all the way from Chicago to the Pacific Coast, instead of five or six as was the practice with steam locomotives. Furthermore, it is possible to increase the fueling and watering points to about 500 miles, thus reducing the stops for this purpose from about 25 to 5.

About five years ago, the General Electric Company began investigating the possibilities of building a steam-turbine locomotive that could be used not only in general

In addition to the results of a firsthand inspection of one of the units of this locomotive, information for this article has been drawn from various authoritative sources, including the railroad company and the manufacturing company principally involved in the development of this significant new motive-power unit. Special credit is acknowledged to the ASME paper by B. S. Cain and A. J. Woodward made available through the courtesy of ASME Editor G. A. Stetson, and the AIEE paper by M. R. Hanna and J. F. Tritle which, together with other references that will serve the reader seeking more details, are listed at the close of the article. The effective assistance of Vice-President H. L. Andrews, Engineer C. M. Davis, and Statistician W. D. Bearce of the General Electric organization in supplying and verifying data likewise is gratefully acknowledged.

railroad service, but also for hauling high-speed passenger trains. Sometime later the Union Pacific also investigated the possibilities of this type of motive power and finally arranged to have a two-unit 5,000-horsepower locomotive of that type constructed. Culminating more than two years of co-operative design and research by scientists, engineers and officials of the railroad and of various manufacturers, this locomotive, which recently was completed and placed in operation, provides the railroads with a new aid to faster schedules and marks another milestone in railroad history.

Each of the two 2,500-horsepower units comprising the 5,000-horsepower locomotive has all the attributes of a straight electric locomotive, and in addition carries its own high-pressure steam-electric generating plant to supply the electric energy required. The locomotive was designed to haul a train of 1,000 trailing tons from Chicago, Ill., to the Pacific Coast by operating the two units in multiple-unit fashion, or either unit may be operated separately to haul a train of half that weight. Maximum speed is 125 miles per hour.

Operating conditions on the Union Pacific System are quite severe. Temperatures vary from −40 to 115 degrees Fahrenheit. Elevations vary from sea level to more than 8,000 feet, and dust imposes a serious problem in some sections. The system also traverses regions in which good water is difficult to obtain. The steam-electric locomotive meets the last difficulty admirably, as the steam plant is a closed condensing system containing less than 3,000 pounds (340 gallons) of water, and requires very little makeup. During the heating season the big demand for water is for steam for train heating, for which a capacity of 3,000 pounds per hour is provided. Each 2,500-horsepower unit carries but 4,000 gallons of raw water—only 1/20th as much as a comparable side-rod steam locomotive. Runs of from 500 to 700 miles may be made without stopping for either fuel or water.

The locomotive is completely controlled from the operator's cab of either unit. Acceleration control may be either automatic or manual, as desired. Under automatic operation, the operator may pull the controller handle immediately to the highest speed position, or to any intermediate position, and the control will accelerate the train at the maximum rate, switching motor connections and raising the motor voltage automatically so as to use all available power at all times. Steam flow from boiler to main turbine is governed by the power demand; feed water, fuel oil and combustion air are controlled in turn by the steam flow, all three being supplied from a single turbine-driven combined auxiliary set.

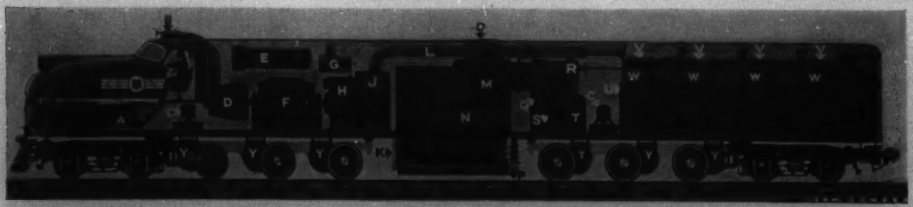
To obtain the capacity, flexibility, and efficiency essential to the best train-operating characteristics, the equipment has been designed to respond promptly to sudden demands for power. For example, following a sudden demand for full output from no load, the boiler pressure may drop to about 1,300 pounds per square inch, but will recover to full rated pressure of 1,500 pounds in less than two minutes, even though under load.

Electric braking is provided, the six propulsion motors on each unit acting as generators and feeding into a water-cooled resistor. It may be used either alone or in combination with train brakes during normal stops or slowdowns, and is particularly advantageous when descending long grades. For example, electric braking has held the locomotive and a trailing train of 1,000 tons on a long 2.2-per cent grade without any application of the air brakes.

General Design of Locomotive

Arrangement of the principal equipment on the steam-electric locomotive is shown in an accompanying illustration. The essential parts of each unit are:

1. A high-pressure oil-burning steam boiler.
2. A turbine-driven auxiliary set to supply feed water, combustion air, and fuel oil to the boiler.
3. Complete automatic control for supplying adequate steam as demanded.
4. A main geared d-c turbine generating set for traction power.
5. An a-c generator on same shaft for train air conditioning, traction motor blowers, and other accessories.
6. Air-cooled condensers for returning used steam to boiler as water.
7. Six axle-hung traction motors geared to main drivers.



Phantom view of locomotive showing general arrangement of parts

A—Raw-water tank
B—Vertical headlight
C—Traction-motor blowers
D—Air-conditioning alternator
E—Train-heating evaporator
F—Main generators
G—Air-brake compressor
H—Reduction gear
J—Main turbine
K—Main control contactors
L—Exhaust header
M—Boiler
N—Feed-water heater
O—Stack
P—Braking resistors
Q—Boiler draft fan
R—Condenser-fan turbine
S—Feed-water pump
T—Boiler-auxiliary-set turbine
U—Fuel tanks
V—Condenser fans
W—Air-cooled condensers
Y—Traction motors

8. Main control system for automatic and manual control of motor combinations during acceleration.

9. Braking-control system which automatically or manually blends electric braking with air braking.

10. Electric couplers and accessories which permit operating the locomotive units singly or in multiple-unit fashion during acceleration and braking.

11. Three separate train-control signal systems to conform to the requirements of the different lines over which the locomotive will operate.

Steam Plant and Cycle

The boiler delivers steam at a pressure of 1,500 pounds per square inch and a temperature of 920 degrees Fahrenheit; it is fired by two vertical oil burners using a low grade of fuel oil known as "bunker C" oil. The furnace has water-cooled walls consisting of six circuits of carbon molybdenum steel tubes coated with refractory. After leaving the furnace, the gases pass through a screen section and up through the economizer, superheater, and air heater to the stack.

From the boiler, steam goes to the main turbines and then to the condensers. The condensate drains to a low-level tank, from which it is pumped to a high-level tank. The high-level tank feeds by gravity into a booster pump which supplies the main high-pressure feed pump. This feed pump returns the condensate through a three-stage feed-water heater to the boiler.

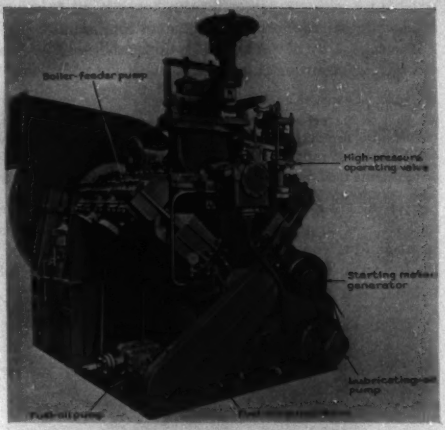
Steam is extracted from the first stage of the high-pressure turbine to drive the auxiliary turbine and condenser-fan turbine, which are connected in series and exhaust into the main condenser. First-stage extraction steam also is used to heat an evaporator supplying make-up and train-heating steam. When insufficient extraction steam is available for these purposes, high-pressure steam automatically is supplied through the auxiliary set and evaporator-control valves.

Three additional extraction lines from the main turbine are used for feed heaters and for controlling the auxiliary-set and condenser-fan turbines. Vacuum is obtained by two ejectors operated from evaporator steam. The condensate pump also feeds the water-cooled braking resistor. Pressure required to force the water through the tubes of the braking resistor is obtained by two injectors using high-pressure steam, and the resistor discharges into a separator from which water returns to the low-level condensate tank and steam to the main condensers.

The closed system contains less than 3,000 pounds of water and, under full load, the water completes the cycle in about $3^1/_2$ minutes.

Summarized Data for Each 2,500-Horsepower Unit of Union Pacific-General Electric Steam-Electric Locomotive

Wheel arrangement	2-C-C-2
Total weight with full tanks of fuel and water, pounds	548,000
Weight on driving wheels, pounds	354,000
Weight per driving axle, pounds	59,000
Fuel-oil capacity, gallons	3,000
Water capacity, gallons	4,000
Total length over couplers	90 ft. 10 in.
Over-all width (including grab handles)	10 ft. $8^1/_4$ in.
Maximum height above rail	15 ft. $^1/_4$ in.
Maximum rigid wheelbase	13 ft. 4 in.
Diameter of driving wheels, inches	44
Diameter of guiding wheels, inches	36
Rated output of main turbine for traction, horsepower	2,500
Turbine speed (constant), revolutions per minute	12,500
Gear reduction to generator shaft	10.4/1
Boiler steam pressure, pounds	1,500
Total steam temperature, degrees Fahrenheit	920
Water in closed boiler-condenser system, gallons	340
Rated output of evaporator for train heating, pounds per hour	3,000
Generator speed, revolutions per minute	1,200
Maximum generator voltage (2 armatures in series)	1,340
Maximum generator current, amperes	3,200
Number of traction motors	6
Weight of each traction motor (less gearing), pounds	10,500
Nominal rating of each traction motor, horsepower	600
Traction motor gear ratio	2.097/1
Starting tractive effort, pounds	86,500
Continuous tractive effort:	
24 miles per hour, pounds	32,000
60 miles per hour, pounds	13,050
100 miles per hour, pounds	7,520
Maximum braking effort available, pounds	35,000
Braking resistor, power absorption capacity, kilowatts	3,600
Maximum permissible speed, miles per hour	125



End view of boiler-auxiliary unit

Steam Control

The amount of water delivered to the boiler is determined primarily by the steam flow, as measured by a steam-flow meter. This measurement is used to control the auxiliary-turbine steam valve and thus controls the speed of the feed-water pump and hence its output. As a further check, the water level in the separating drum is measured and this measurement, serving as a final correction on the water flow, also is relayed to the auxiliary turbine. The fuel-oil pump and combustion-air blower are both driven by the same auxiliary turbine that drives the feed-water pump. They are proportioned so that for a speed suitable to deliver the required quantity of water, they will deliver an excess of oil and air above the quantities required to generate steam from that water. The excess capacity is throttled, the oil by a valve and the air by a damper which has its position modified in accordance with steam pressure. The fuel-oil valve is controlled in

accordance with the metered ratio between oil flow and air flow to maintain proper combustion conditions.

The continuity of combustion is under the control of an electric circuit arranged to:

1. Ignite or extinguish the fire in operating.
2. Shut off the fuel in the event of high steam pressure, high steam temperature, flame failure from any cause, or failure of water supply or lubricating-oil supply to the feed pump.
3. Re-ignite the fire when normal conditions are established.

Propane gas ignited by spark plugs serves to ignite the fuel oil. With all conditions normal, the propane is ignited and after a few seconds the fuel-oil valve is opened. Photoelectric cells located to receive light from the oil

Main double-armature 2,500-horsepower generator

fire operate to shut off the igniting torches when normal fire is established. They also shut off the fuel supply and initiate a normal igniting cycle in case the fire goes out. In cases such as lack of fuel oil, the igniting cycle will repeat four times, then lock out until manually reset.

The time required to build up full steam pressure and make the locomotive ready for service is only 15 minutes. Hence, there is no need to use fuel to keep the locomotive hot when not in service.

In addition to the main boiler control, the automatic system maintains water level in the condensate tank, admitting steam from the evaporator to the closed system when the water is low, or returning water to the raw-water tanks when the level is too high. The condenser-fan speed is controlled automatically by the temperature of the condensate return from the condensers. The evaporator also has its own control, which maintains water level and steam pressure in the evaporator shell.

Boiler Auxiliary Set

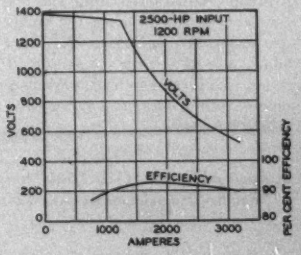
The boiler auxiliary set is essentially a variable-speed unit, its speed depending on the load on the boiler; it is turbine driven and supplies feed water, combustion air, and fuel oil to the boiler. The turbine has a four-stage rotor and is geared to the feed pump and blower. The auxiliary set has a geared battery-operated starting motor which also acts as a generator driving the other motor pumps after the auxiliary turbine is on steam, in case the battery-charging set is not running.

The steam condenser is built in 24 sections and mounted in the rear of each locomotive unit. Each section consists of vertical finned tubes between upper and lower headers. The sections are of two-pass design, the first pass being primarily for condensation of steam and the second pass primarily for cooling of air and vapor which are drawn off by the ejectors. The upper headers are thus divided into steam and air sections and the lower headers are drained to the condensate return lines.

Four 65-inch aphonic fans on each locomotive unit provide air to cool the condensers. The fans are driven from one turbine through a line shaft and four right-angle-drive gear boxes. The turbine, which takes steam from the auxiliary-turbine exhaust and discharges into the condenser, is mounted on the boiler auxiliary set. It is a 3-stage single-reduction-gear unit.

Main Turbine-Generator Unit

Four units comprise the main turbine-generator set; a geared turbine, a main d-c generator, an auxiliary alternator, and an exciter. The turbine is a two-cylinder ten-stage cross-compound machine with two pinions running



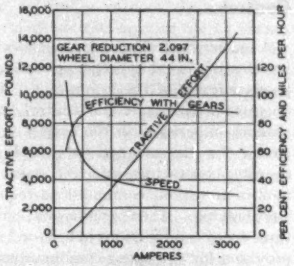
Characteristics of main 2,500-horse-power generator with speed control

on a common gear. Turbine rotor speed is 12,500 rpm, which is reduced to 1,200 rpm by the reduction gear. The geared turbine is connected through a flexible coupling to the main d-c generator.

A pair of complete generators built in a single frame with armatures back-to-back comprise the main d-c generator. To provide rigidity with minimum weight, the tandem armatures are built on a single hollow steel cylinder with stub shaft extensions at each end. To avoid excessive commutator surface speed, it was necessary to reduce the commutator diameter to a point that precluded passing the armature ventilating air under the commutators. Ventilation is effected through the risers, which are of the involute type to serve also as equalizers. The armature ventilating fan is mounted in the central space between the two armatures.

These two component generators built into one frame are normally connected in series with their midpoint

grounded, thus limiting the insulation stress in all the transmission equipment to not over half the total voltage generated. The traction generator unit is separately excited by a "metadyne," or variable-voltage, exciter, which, through a speed-sensitive control device and depending on the turbine power available, imparts to the generator output characteristics as shown in an accompanying graph. The electrical proportions of the machine are such that it



Characteristics of traction motor on 300 volts

will produce full horsepower continuously at any point shown on these characteristic curves, from some 1,300 amperes at 1,320 volts to 3,200 amperes at about 520 volts. Maximum generator voltage is 1,400 volts.

Auxiliary A-C Generator, and Exciter

The auxiliary a-c generator and the main-generator exciter are built into a compact two-unit machine having a centrally located ventilating fan and a single self-aligning antifriction bearing, the driven end of the set being supported on a steel disk type of flexible coupling through which the auxiliary unit is attached to a shaft extension of the main generating unit. The a-c machine is of the salient-pole-rotor design with distributed stator windings. The continuous rating is 480 kva, 230 volts, three phase, 60 cycles. It is of conventional design except for the use of class B insulation and aluminum frame to reduce size and weight. The primary purpose of the alternator is to supply lighting, heating, cooking, and air-conditioning power to streamlined passenger trains. On the locomotive it supplies two traction-motor blowers, the speed-control governor, the main air compressor, the 130-volt and 64-volt motor generator sets, and, through small transformers, the 12-volt headlights and part of the 115-volt lights.

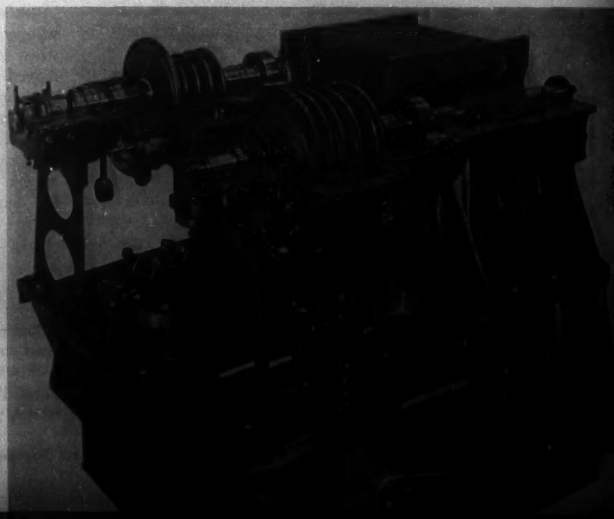
In common with all "metadyne" type machines, the exciter is characterized by armature excitation. One of its most valuable properties lies in its inherent characteristic of delivering a definite current output regardless of load-circuit resistance, the value of the current being approximately proportional to the current in one of its low-wattage control fields. This exciter has two distinct functions. During the normal operation of the locomotive as a propulsion unit, it excites the field of the main traction generator. However, in electric braking, the exciter output connections are transferred from the generator fields to the traction-motor fields. It is here (as well as for multiple-unit propulsion operation) that the inherent constant-current characteristics of this exciter are of special value, for while the resistance of the traction-motor fields may change due to variations in temperature, the braking characteristics remain essentially unaltered.

Traction Motors

A locomotive with a weight of 354,000 pounds on its six driving axles and an operating range extending from a maximum speed of 125 miles per hour at one extreme to a maximum tractive effort of nearly 90,000 pounds at the other, presents a broad problem in traction-motor design. As usual in traction motors, much of the design was dictated by the necessity of mounting the motors between the wheels on standard track gauge. Minimum weight is of paramount importance. The motors are axle mounted, thus permitting the use of small wheels (44 inches). This gives the lowest possible cab floor height and the maximum room for apparatus in the cab. Characteristics of the traction motors on constant voltage are shown in an accompanying graph. The motor has eight poles with multiple-wound fully equalized armature.

In service the motors operate on a constant-horsepower variable-voltage generator characteristic, and the six motors in each locomotive unit will transmit 2,500 horse-

Main turbine and gear partially assembled; height of the portion shown is approximately five feet, which gives an indication of the compactness of the unit



power turbine output at any speed up to 125 miles per hour. Each motor is normally supplied with 2,000 cubic feet of cooling air per minute. The normal continuous rating is 32,000 pounds tractive effort per locomotive unit. To permit the handling of heavy trains in transcontinental service without the use of helper locomotives on heavy grades, high speed operation of the traction blowers is provided, giving 4,000 cubic feet of ventilating air per minute per motor. The rating obtained with this ventilation is 40,500 pounds tractive effort per locomotive unit.

Braking Resistor

Approximately 350 feet of seamless drawn stainless steel tubes through which cooling water is circulated comprise the braking resistor. These tubes are connected at the ends by cast return bends of the same material and the complete unit is assembled on insulated supports in the

Water-cooled braking resistor; this is mounted horizontally underneath the locomotive

form of an oblong spiral. The tubing is arranged in two parallel hydraulic circuits with separate inlets and a common outlet which is rigidly grounded. Inlet pipes are insulated from ground by a special high-temperature molded tubing.

Ahead of each insulator tube is mounted an injector, supplied by steam from the main boiler and designed to force the cooling water through the braking resistor. The resistor has capacity to dissipate 3,600 kw continuously, but this maximum rating is used only when decelerating trains from maximum speeds. When braking at maximum capacity, approximately half the cooling water is converted into steam and the mixture passes through a steam separator; the water is returned direct to the hot well and the steam is passed into the main condenser.

Miscellaneous Electrical Equipment

Other electrical or electrically driven equipment on the locomotive includes:

1. A two-stage air compressor having a piston displacement of 186 cubic feet per minute to furnish air for braking and control apparatus; this unit is driven by a three-phase 60-cycle 220-volt induction motor, through herringbone gearing.
2. Two d-c motor-driven compressors with a combined piston displacement of 36 cubic feet per minute to charge the control system for initial start of the locomotive before steam is generated, and to assist in supplying air to the main reservoir when demands are heavy.
3. A 40-kw 130-volt d-c generator driven by a three-phase induction motor for charging storage batteries, supplying electrical control, boiler control, miscellaneous pumps, and other auxiliary circuits.

Control

A master controller with three mechanically interlocked handles to prevent improper operation controls all the main power circuits of the locomotive. The motoring handle operates a cam shaft and control fingers which vary resistance in series with the exciter field and establish the circuit for the magnet valves of electropneumatically operated contactors which connect the main traction motors in various combinations required for accelerating and braking. These contactors connect the motors in three speed combinations of 6, 3, or 2 motors in series, with provision for two speed combinations of 4 and 2 in series with any pair of motors cut out. Transition resistors are used to prevent interruption of power to the motors during transfer of the motors from one combination to another.

The brake handle drives its control cylinder through a long spring mounted concentric with the operating shaft. When this handle is moved into any one of the 20 notches on its dial ring, the spring will exert a torque to turn the control cylinder through the gear and sector at the bottom of the controller to the position selected on the dial ring. The movement of the cylinder, however, is governed by the notching mechanism engaging the notched wheel on the end of the shaft. The notching mechanism is controlled by current and kilowatt relays connected in the motor circuits during the braking cycle.

A seven-position selector handle governs the various series and parallel traction-motor connections for both forward and reverse directions. When accelerating the train from rest, this selector handle is moved to the "parallel" position, although with the automatic control in operation the motors actually are connected in series when starting from rest; the motoring handle then is moved slowly through the first few notches to take up slack and get the train into motion, after which it may be advanced as rapidly as desired up to the last, or 21st position. The movement of the motoring handle cuts out sections of fixed resistance in series with the field of the exciter. However, the exciter field current is limited by the automatic load-regulating equipment which takes control as soon as the motoring handle cuts out sufficient resistance to permit regulation at all output. Transition of the motors from series to series-parallel and from series-parallel to parallel takes place automatically under the control of a voltage relay when the generator voltage reaches the proper predetermined value. If it is desired to start and operate a train at less than full speed, the selector handle may be placed either in the "series" or "series-parallel" position, which prevents the motors from transferring to the next highest speed combination. The

main handle, of course, may be notched backward or forward at will to maintain any desired train speed.

If for any reason the operator wishes to eliminate the automatic features, a switch may be thrown which bypasses the automatic devices and cuts out the automatic transitions.

Braking may be controlled either manually or automatically. Manual control of the electric brake is provided to permit its use for slowing down the train and for controlling the speed on grades without the use of air brakes. This arrangement permits keeping the air brakes in reserve when descending long grades and relieves the wheels and brake shoes of considerable duty during slowdowns, particularly from high speeds. The advantages of such operation are apparent both from the standpoints of safety and brake maintenance. When curves permit, it is also possible to descend grades at higher speeds with safety because the air brakes are in reserve for stopping in an emergency.

The locomotive is equipped with "automatic air-brake control equipment" for conventional steam trains and "high-speed straight air-control equipment" for use on streamlined trains. Automatic control of the electric brake may be used in combination with both systems. When used, the full capacity of electric braking is available, assisting the air brakes in slowing down and stopping the train (electric braking is effective at all speeds down to about five miles per hour). The arrangement is such that air pressure to the driver brake cylinders is suppressed when the electric brake is functioning normally.

Every effort has been made to provide the greatest flexibility possible in the control of the electric brake, both separately and in combination with air, so that full advantage can be taken of this new type of braking under all operating conditions.

Train Control. The locomotive is equipped with three separate train-control systems to conform to the different lines over which it will operate. A two-indication continuous-cab-signal system with two-speed control is provided for operation over the lines of the Chicago and North Western Railway. A two-indication continuous-cab-signal system with whistle and acknowledging feature is included for use on the lines of the Union Pacific Railroad. An intermittent magnetic inductive automatic stop system is provided for use on the Southern Pacific.

Comparative Costs

Although it is too early to make accurate comparisons of initial and operating costs between the steam-electric and other types of locomotives, a few approximations may be of interest. Under normal shop-production conditions, it is expected that steam-electric locomotives of this type can be built at a cost not more than twice that of a reciprocating steam locomotive, or about the cost of a Diesel-electric.

Fuel costs of the steam-electric unit are expected to be not more than 60 per cent of the fuel cost for a reciprocating steam locomotive and slightly less than the fuel cost for a Diesel-electric unit. Although the efficiency of the steam-electric is somewhat less than that of the Diesel-electric, the lower grade of fuel oil used is less expensive, thereby allowing the cost of fuel for the steam-electric to be slightly less than that for the Diesel-electric.

Other advantages of the steam-electric locomotive that have a direct bearing on the over-all cost are its high availability, ability to run long distances with short terminal layovers, low water consumption, and expected low maintenance cost. In addition, its uniform balanced drive and moderate axle loading tend to promote safety and decrease track maintenance.

References

1. Steamotive—A Complete Steam-Generating Unit, Its Development and Test, **E. G. Bailey, A. R. Smith,** and **S. P. Dickey.** *Mechanical Engineering*, volume 58, December 1936, pages 771–80. Preliminary mechanical and test data.

2. The Steam-Electric Locomotive for the Union Pacific Railroad, **W. D. Bearce.** *General Electric Review*, volume 42, February 1939, pages 87–91. Brief general description.

3. Electrical Equipment of the Union Pacific Steam-Electric Locomotive, **M. R. Hanna** and **J. R. Tritle.** A paper presented at the AIEE combined summer and Pacific Coast convention, San Francisco, Calif., June 26–30, 1939, and scheduled for publication in AIEE Transactions, volume 59, 1940.

4. Design of the Union Pacific Steam-Electric Locomotive, **B. S. Cain** and **A. J. Woodward.** A manuscript scheduled for publication by The American Society of Mechanical Engineers in a late 1939 issue of *Mechanical Engineering*. Concerned principally with the mechanical design.

The old and the new; left to right: a wood-burning steam locomotive used in 1865 by the Union Pacific Railroad; the new 5,000-horsepower steam-electric locomotive; Diesel-electric locomotive of the crack passenger train "City of Los Angeles", and at the extreme right a large modern reciprocating steam locomotive

Mechanical Demonstrator of Traveling Waves

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MEMBER AIEE

By means of the device described in this article, which simulates in a mechanical sense the electrical phenomena of traveling waves on power-transmission lines, various types of surges may be visualized and relations fundamental in transmission theory may be deduced.

COLLEGE PROFESSORS are invariably of the opinion that demonstration equipment, by visualizing to the observer the actual operation of the equipment, is of considerable aid to the understanding of the phenomenon involved. Analogies, by arguing from the known to the unknown, or from the familiar to the unfamiliar, are of additional assistance. It is frequently possible through the use of an analogy to illustrate a phenomenon visually that under other circumstances would be somewhat abstract. This is particularly true of mechanical analogies of electrical phenomena; one cannot see electromotive forces or currents, but can see the physical movement of mechanical bodies.

The simplest mechanical analogy, one with which almost everyone is familiar, consists of the simple spring, mass, and damping element which is used to simulate the electrical equivalent of capacitance, inductance, and resistance. These equivalents are illustrated in figure 1. The force required to stretch a spring is proportional to the displacement; but since the displacement is the integral of the instantaneous velocity, v, the force can be expressed by $K\int v dt$. Similarly, the force exerted by the inertia of a mass is proportional to the acceleration and can be expressed by $M\,(dv/dt)$. A pure damping element must be so constructed that the force exerted by it is proportional to the velocity $K_d v$. Turning to the electrical system one finds similar relations. The voltage drops across a capacitor, inductor, and resistor are equal, respectively, to $(1/C)\int i dt$, $L(di/dt)$, and Ri. By comparing these expressions it can be seen that if capacitor, inductor, and resistor of the electrical system be replaced by spring, mass, and damping element of the mechanical system the forces across the mechanical elements are the same functions of v as the voltage drops across the corresponding elements of the electrical system are of i. The third column depicts the corresponding counterparts of the mechanical system for rotary motion.

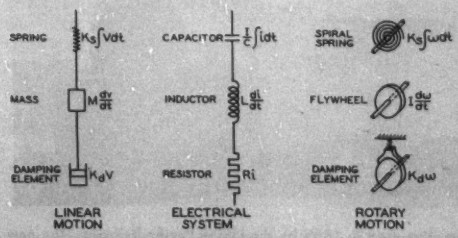

Figure 1. Correspondence between electrical and mechanical systems

A transmission line can be conceived as being made up of elements of series resistance and reactance with capacitance in shunt. The effect of series resistance is to produce both attenuation and distortion of the wave. For several span lengths, however, both these effects are negligible, and in this discussion a resistanceless line is premised.

A resistanceless line can be simulated in the mechanical analogue by means of elements of the type shown in figure 2. Each element consists of an aluminum arm, mounted at its center of gravity, upon two pivot bearings of hardened steel. Near the point of mounting, a flat steel spring is fastened securely. The free end of the spring is secured to the end of the adjacent arm. Fifty-six such arms mounted in the manner described are shown in figure 3. This constitutes the main portion of the demonstrating device. In each element the mass of the arm corresponds to the inductance of the line and the spring to the shunt capacitance. The friction of the mounting has been kept to a minimum. The little friction that remains corresponds in the transmission line to shunt or leakage resistance. Apparatus of this general character is not new, as evidence the vertical mechanical wave machine which is in practically all physics laboratories and also the wave machines on demonstration at the Franklin Institute. It is believed, however, that this particular model lends itself better than others to the demonstration of the electrical problems discussed in this article.

Figure 2. One element of wave demonstrator

For some of the demonstrations to be discussed it is necessary to simulate shunt-connected resistances on the transmission line. Referring to figure 1, it may be seen that these can be simulated by a device in which the force exerted is proportional to the velocity. For this purpose small single-phase squirrel-cage induction motors are utilized. These motors are excited by direct current

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instead of alternating current, the source being six dry cells. Because of the constant field, any motion of the rotor develops in the rotor an electromotive force that is proportional to the instantaneous value of the velocity. At the frequencies involved, or, stated more accurately, for the velocities involved, the inductive drop in the rotor is negligible so that the current in the rotor is determined purely by the electromotive force and the rotor resistance. The reaction of the rotor current with the magnetic field then produces a retarding force or torque proportional to the stator current and the instantaneous velocity of the rotor. This is just the characteristic required by the relations of figure 1. The effect of different resistances in the electrical system is obtained simply by varying the stator current. These elements, of which there are four, are mounted on a lower angle section as shown in figure 3. When desired they may be connected to the arms by means of the strings (figure 4) which transfer the rotary motion of the arms to that of the rotors of the motors. They have been placed on the lower bracket instead of directly on one of the arms for several reasons: First, the weight of the rotor is more than a delicate arm bearing would withstand; second, there would be insufficient space on one of the arms; third, the string connection permits amplification of the motion.

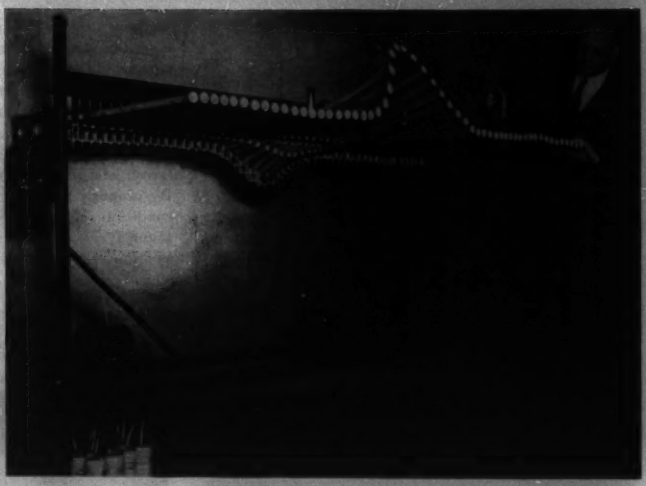


Figure 3. General view of wave demonstrator being operated by author

With the device just described it is possible to illustrate many of the phenomena associated with the problem of traveling waves, including reflections at transition points, effect of tower-footing resistance, and the like. Further, arguing from experiment, it is possible to derive most of the fundamental laws of traveling waves. In the absence of direct visual testimony in a written description, some of these experiments are shown by a succession of frames taken from a motion picture. Unless otherwise stated, the resistance elements are assumed to be disconnected from the line.

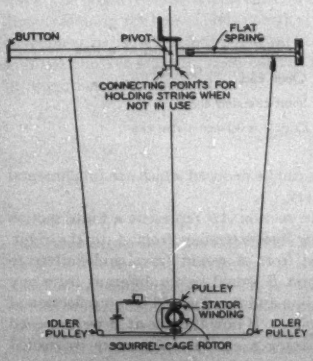


Figure 4. Schematic diagram of damping element which simulates shunt resistance

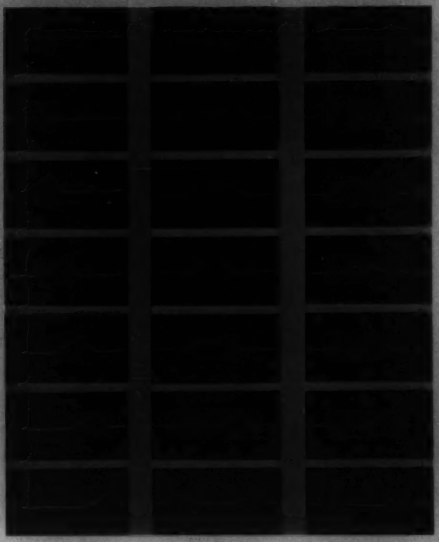
Simple Wave Motion

If this system is disturbed by moving the end element manually in a vertical direction, the motion is propagated along the row of arms in the form of a wave, the shape of the wave and its amplitude being maintained as the wave progresses along the line. The nature of the propagation is depicted in figure 5 which shows successive positions of the wave. This is true regardless of the shape of the wave impressed upon the device.

It is apparent that if the mass of each arm in the device is increased the motional response of an arm to the deflection of its spring will be slower. A disturbance then would be transmitted from arm to arm at a slower rate and the velocity of propagation of the wave would be slower. A similar result occurs in an electric line with distributed constants if the inductance (or mass) is increased. This relation is in accordance with the quantity $1/\sqrt{LC}$, which expresses the velocity of propagation of the wave in a line. By varying the mass of the arms and the stiffness of the springs this relation can be verified experimentally.

Waves Passing Through Each Other

The performance of two waves that reach a point from two different directions is interesting. Their action is



(a) (b)

Figure 5 (left). Simple wave motion

Figure 6 (a and b). Two waves passing through each other

(a) Two positive waves

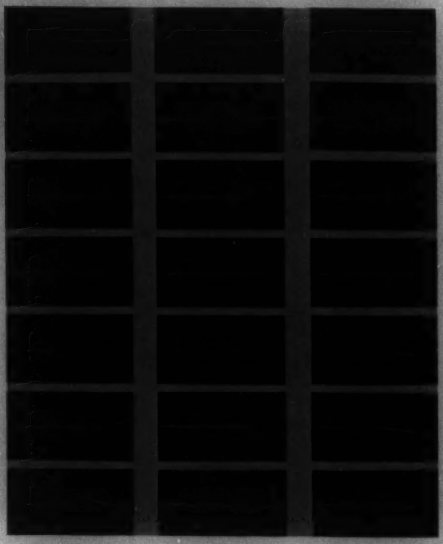
(b) One positive and one negative

shown in figure 6*a*. It may be seen that both waves pass through each other with unchanged amplitudes and wave forms. During the period of passage the amplitudes are additive. Figure 6*b* shows a similar phenomenon in which one of the waves is positive and the other negative.

Reflections at the Ends of Lines

There is perhaps no more important phenomenon in the theory of traveling waves than that of the reflections at the ends of lines. Consider first an open-circuited line. This corresponds in the mechanical analogue to the condition in which the end arm is permitted to swing freely. As shown in figure 7*a*, the reflected wave has the same shape and amplitude and also the same polarity as the oncoming wave. In addition, the maximum voltage at the end of the line is equal to twice the maximum value of the oncoming wave. Since the waves under discussion are voltage waves, then a short-circuited line can be represented by constraining the end arm from moving. This is easily accomplished by clamping the end arm in position. The result for this case is shown in figure 7*b*, where the reflected wave has the same shape and amplitude as the oncoming wave, but the opposite polarity.

A line terminated by a resistance is represented in the mechanical analogue by connecting one of the previously described damping elements to the end arm. When the current in the stator is small, that is, the damping is small, a high resistance is simulated and the reflected wave is of the same form and polarity as the oncoming wave, but the amplitude is smaller. When the current in the stator is large, the reflected wave has the same shape, opposite polarity, and smaller amplitude than the oncoming wave. By properly adjusting the stator current, or damping, a condition is attained for which there is no reflected wave (figure 7*c*). It follows then that for an actual transmission line there exists a particular critical resistance which when connected in shunt across the terminals at the end of the line results in no reflected wave when an oncoming wave strikes the end; the wave is completely absorbed. This condition is extremely interesting and from it several



(a) (b) (c)

Figure 7. Reflections at the end of a line

(a) Open end

(b) Short-circuited end

(c) Critical resistance across end

important relations can be deduced which are fundamental in transmission theory.

In figure 8 let the section AB represent a finite section of an infinitely long line extending from A to the right. A wave propagated from A would travel indefinitely to the right. The point B would be no different from any other point on the line and there would be no reflection of the wave at that point. If now the line at B were opened and a resistance having a critical value were connected

across the open end at B, then likewise there would be no reflection at B to an oncoming wave. This shunt resistance then must perform in all respects as the infinitely long line from B to the right. It is known that the current in the resistor must be proportional at any instant to the voltage across it; more specifically the current must be equal to e/R_c, where e is the instantaneous voltage and R_c is the value of the critical resistance. It follows, therefore, that in the infinitely long line a current must flow that is related at any instant to the voltage by the same relation. This is a fundamental of all traveling-wave theory—that a current wave of the same wave form attends all voltage waves. A particular name, the surge impedance of the line, and particular symbol, Z, have been given this critical resistance; it can be shown to equal $\sqrt{L/C}$, where L and C are the inductance and capacitance, respectively, per unit length of line. As can be seen from the experiment in which the resistance R_c is connected across the line, the direction of propagation of the wave in the line corresponds to that of the direction of current flow, that is, a positive voltage wave produces a positive current flow in the direction of propagation of the wave.

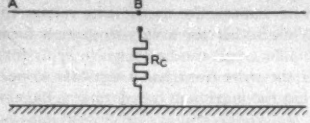


Figure 8. Diagram to prove that current wave of same shape accompanies voltage wave

With this conclusion it is possible to extend what has been proved here regarding wave theory. Assume a forward moving wave e_f. It will have associated with it a current wave i_f equal to e_f/Z. A backward moving wave e_b would have associated with it a current wave e_b/Z in which the positive sense of current flow is in the backward direction along the line. For analytical use it is rather inconvenient to have different positive senses of current flow, so if the positive sense for both current waves is chosen as the direction of the forward wave,

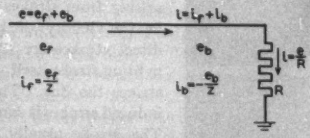


Figure 9. Schematic diagram of transmission line terminated by a shunt resistance R

$$i_f = \frac{e_f}{Z} \tag{1}$$

and

$$i_b = -\frac{e_b}{Z} \tag{2}$$

In general two waves of this nature can exist simultaneously, as was illustrated in several of the experiments, the most outstanding in this regard being the one in which two waves traveling in opposite directions passed through each other.

If a line is terminated by a resistance R, both an oncoming and a reflected wave appear. If these are given the designation shown in figure 9, then at the end of the line the total current, i, is equal to

$$i = i_f + i_b = \frac{e_f}{Z} - \frac{e_b}{Z} \tag{3}$$

Similarly, the total voltage at the end of the line is

$$e = e_f + e_b \tag{4}$$

But this voltage is also equal to the drop across the resistance, and since the total current must flow through the resistance

$$e_f + e_b = Ri \tag{5}$$

Substituting from equation 3,

$$e_f + e_b = R\left(\frac{e_f}{Z} - \frac{e_b}{Z}\right) \tag{6}$$

Solving this equation,

$$e_b = \frac{R - Z}{R + Z} e_f \tag{7}$$

This result has been obtained without recourse to any mathematics higher than just simple algebra. By means of this equation the experiments just performed for open-ended lines, short-circuited lines, and other conditions can be checked.

Power loading of an a-c line must be accompanied by a phase displacement between the voltages at the two ends of the line. The truth of this statement can be demonstrated best by considering the performance of the mechanical analogue loaded by its critical damping element when a continuous alternating disturbance (alternating voltage) is applied at the sending end. Because of the absence of reflections the waves continue to travel along the line without distortion at their natural speed. This is shown in figure 10. The performance should be independent of the frequency except that the waves would be crowded closer together at the higher frequencies. In an actual line the distance between nodes is equal to the distance the wave can move in one cycle. Thus for a 60-cycle wave the distance between nodes, or the wave length, is equal to the velocity of light (186,000 miles per second) divided by 60, or 3,100 miles. In other words, a 3,100-mile line would have a phase displacement of 360 degrees. Shorter lines would have phase displacements in proportion. A 200-mile line, for example, would have a phase displacement of (200/3,100) × 360 or 23 degrees. For larger loads, that is, smaller values of terminating resistance than the critical value premised,

Figure 10. Voltage distribution with sustained alternating potential at sending end of a line terminated by a resistance having the critical value

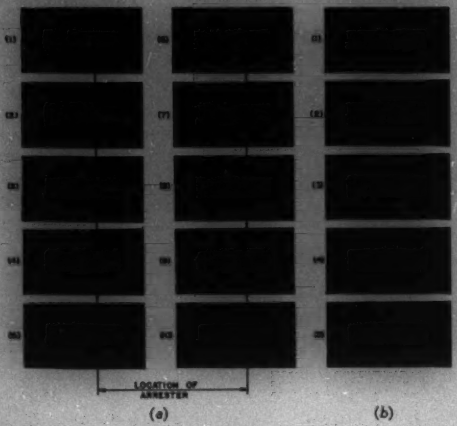


Figure 11. Operation of a lightning arrester in limiting the voltage on a transmission line

(a) Arrester at some distance from end of line

(b) Arrester at end of line

this angle is greater, and for smaller loads, that is, larger resistances, it is smaller. This raises a point that has given some persons considerable trouble. It is frequently argued that, since electricity travels with the speed of light, at no load the phase displacement between the voltages at the two ends of the line must be that corresponding to the time it takes light to travel the length of the line; that is, for a 200-mile line the phase angle must be 23 degrees. This argument neglects entirely the reflections at the ends of the line. It has just been demonstrated that these can be neglected only when they are zero, that is, when the critical damping resistance is connected in shunt across the terminals.

Lightning Arresters

Lightning arresters frequently are used for the protection of transformers. It is important that they be located as close as possible to the equipment to be protected. The truth of this statement can be demonstrated on the mechanical demonstrator in which the lightning arrester is represented by means of a fixed rod which limits the travel of the arm at the location corresponding to that of the arrester. Electrically this corresponds to an ideal arrester for which the voltage is limited to a constant value regardless of the current flow. In other words, the volt-ampere characteristic of this ideal arrester is one in which the voltage is constant regardless of the current. The operation of this device when the arrester is located some distance from the end of the line is shown in figure 11*a*. It may be seen that as a wave approaches the arrester the arrester limits the voltage at that point and permits a flat-top voltage wave equal to arrester voltage to continue beyond the arrester. However, at the end of the line where the transformer to be protected might be located reflection occurs which raises the voltage to twice arrester voltage. This voltage will continue at this value until enough time has elapsed for a wave to be propagated from the end of the line to the arrester and back again. At the end of this time the negatively reflected wave from the arrester reduces the transformer voltage to arrester voltage. While in this case a very steep wave form was premised, a similar result can be shown to apply for waves less steep. If the wave front has a constant slope, it can be shown that the maximum transformer voltage is equal to

$$e_a + 2\frac{de}{dt}\frac{D}{1{,}000}$$

where e_a is the arrester voltage, de/dt is the slope of the oncoming surge in volts per microsecond, and D is the distance in feet between arrester and transformer.

If, however, the arrester is located at the end of the line it will not offer adequate protection to a transformer that is located out on the line too far. This likewise can be demonstrated on the mechanical device as shown in figure 11*b*. If the transformer is located out on the line too far the voltage across it will not be influenced until the negative reflected wave from the arrester has had an opportunity to reach the transformer. For a flat-top wave the transformer then would have a very high voltage applied to it for a time equal to the time required for a voltage wave to propagate from the transformer to the arrester and return.

Induced Lightning Stroke

Surges on transmission lines due to lightning may originate in either of two ways, namely, induced surges or direct strokes. Induced surges are those arising from strokes to other objects in the vicinity of the line, whereas direct strokes are those in which the lighting stroke itself or a side streamer strikes the line. The mechanism for induced strokes is somewhat as follows. The stroke usually originates at the cloud and propagates earthward at a relatively low speed as compared with that of light. During this process negative charge is lowered from the cloud into an immense antenna-like system of leaders in the air. This process may take a time of the order of 10,000 microseconds. As the downward leader strikes the earth a very brilliant leader is observed to travel upward. The currents associated with this upward leader are of the order of 10,000 to 150,000 amperes. These very large currents result because the same charges that had been lowered during the initial slow process in a time of about 10,000 microseconds are now discharged in the much shorter

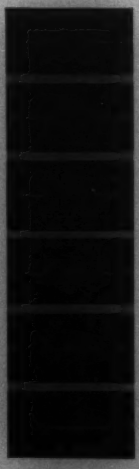


Figure 12. Breakdown of standing wave into two parts

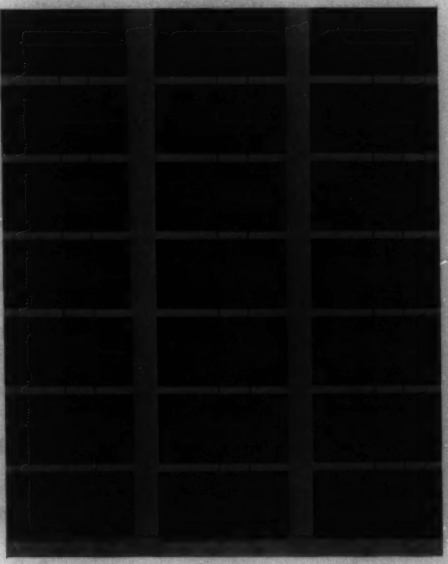
time of the order of 50 to 100 microseconds. While the charges are being lowered, the transmission-line conductors tend to attain a potential that is dependent upon their position. The principal contribution to this potential is that due to electrostatic effects. While these phenomena were considered very important in the early investigations of lightning, subsequent calculations indicate that they were overemphasized, because the mechanism is much slower than had originally been supposed.

In addition to the potentials that are produced by the lowering of the cloud charge there is also the very interesting phenomenon that since these fields are not produced instantaneously but require a finite time, part of the charge induced and the associated voltage produced can leak off along the transmission line. This phenomenon can be demonstrated in part by the wave demonstrator. Consider a wave of the form shown in the upper frame of figure 12. If this voltage is produced by an induced charge upon the transmission line it will exist as shown so long as the charge distribution remains as postulated. However, these charges are free to leak along the line and what happens is that the wave is broken up into two equal components, one traveling to the left and one to the right, the total voltage at any instant being equal to the sum of the two waves.

Direct Strokes

With the knowledge that a lightning stroke may have a potential of 10,000,000 to 20,000,000 volts and the crest value of the 60-cycle flashover of 12 insulators, the number that might be used on a 110-kv line, is only 700,000 volts effective, the question naturally might be raised as to how it is possible to protect such a string of insulators from flashing over. The answer lies primarily in the use of ground wires. For direct-stroke protection they must be so located as to insure interception of the stroke. This assumption is fundamental to the theory. For this purpose they must be located well above and not in too far with reference to the line conductors—a condition in direct conflict with the induced-stroke theory which required that the ground wires be located as close to the conductors as possible in order to increase the coupling. In the induced-stroke theory coupling is of prime importance, but in the direct-stroke theory it is relegated to secondary importance by the necessity of insuring that the stroke hits the ground wire.

Starting with the premise that the ground wire is struck, use can be made of the wave demonstrator to show how the voltage on the ground wire is reduced below that of the stroke voltage. Consider first the case shown in figure 13 in which lightning strikes the ground wire at the tower top. It has become generally accepted that after striking a grounded object the lightning channel might be regarded as any other conductor. While this is not strictly permissible it is sufficiently close to actuality for the present purpose. In addition, a further questionable assumption of



(a) (b) (c)

Figure 14. Potential of ground wire when lightning stroke occurs at a tower top

(a) High footing resistance
(b) Medium footing resistance
(c) Low footing resistance

the negligibility of the tower surge impedance will be made. Only the surge impedance of the ground wires and the tower-footing resistances will be considered. Upon striking the tower the surge divides between the two ground wires and the footing resistance of the stricken tower. The surge impedance of the lightning channel has been variously estimated as from 200 to 600 ohms and the surge impedance of a ground wire as about 400 ohms. Because of the symmetry of the circuit, it is permissible to consider one side of the line folded over onto the other side. The impedance of the two paralleled ground wires then would be 200 ohms and the impedance of each of the footing resistances, except that of the struck tower, would be one-half the single footing resistances. If the stroke impedance is chosen as 200 ohms, a circuit is obtained which can be

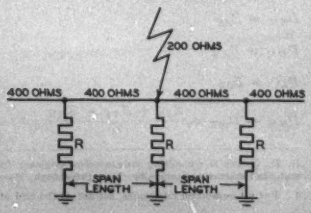


Figure 13. Schematic diagram of circuit when lightning stroke occurs at tower top

represented on the demonstrator. In figure 14 the portion of the demonstrator to the left of the left-hand "T" represents the lightning channel and the portion to the right, the ground wire. At each of the "T's," which represent towers, a damping element is connected to simulate the footing resistances. These elements can be varied to illustrate the effect of different footing resistances.

Figure 14*a* shows clearly how the potential of the first tower top varies when the damping elements are adjusted to represent high tower-footing resistances. It may be observed that the potential remains quite high with respect to the oncoming wave. There is little diminution in its magnitude. Figure 14*b* represents the case for which the footing resistances are smaller. The tower potential is much smaller and it can be observed that after the surge has traveled to the second tower a negative wave is reflected and reduces the potential at the first tower still more. Figure 14*c* shows the phenomenon when the footing resistances are reduced still further. For this case the tower potential is reduced to a very low value. It is important to note that not only is the magnitude of the potential reduced but also the time during which the peak exists is reduced.

In the usual mechanical analogies used to represent transmission lines, voltage is represented by force (or torque) and current by velocity. In this case a rigorous relationship exists for all conditions; in a forward moving wave torque is proportional to the negative of velocity and in a backward moving wave proportional to the velocity; reflections at the ends of lines are correct for resistors, capacitors, or inductors. Visual evidence of the torque is offered by the instantaneous slope. It is difficult, however, as a demonstration device to try to follow visually such variations as a slope or velocity. However, since the displacement is the time integral of velocity or the space integral of slope, the displacement can be used in certain cases to simulate voltage waves. This is permissible when the discontinuities involve resistors only. The truth of this statement may be evident from the fact that the first derivative of the reflected wave is proportional to the first derivative of the oncoming wave and therefore their integrals, which are the waves themselves expressed as displacements, are also proportional. With discontinuities involving capacitors and inductors, the proper similitudes exist for the velocities and slopes of the oncoming and reflected waves but not for their integrals.

Simplified Computation of Voltage Regulation

With Four-Winding Transformers

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COMPUTATIONS of voltage regulation ordinarily are based on the use of an equivalent circuit for the four-winding transformer, using either a six-branch network, or preferably the eight-branch network described by Starr.[1] Determination of the equivalent circuit—a tedious analytical task—appears to be unnecessary, however. As a simpler alternative for determining voltage regulation with load on three windings and the fourth winding acting as a source, the necessary constants may be obtained directly from the usual two-terminal impedances.

For example, assume a four-winding transformer with loads, impedances, and terminals designated as shown in figure 1. The two-terminal impedances are assumed to be available from calculations or tests, and to be reduced to a common kilovolt-ampere and voltage base. The voltage drops to terminals H, M, and L may be computed from the following equations:

$$E_H = E_S - D_{HH}I_H - D_{HM}I_M - D_{HL}I_L \quad (1)$$

$$E_M = E_S - D_{MH}I_H - D_{MM}I_M - D_{ML}I_L \quad (2)$$

$$E_L = E_S - D_{LH}I_H - D_{LM}I_M - D_{LL}I_L \quad (3)$$

in which D_{HH}, D_{HM}, D_{HL}, D_{MH}, D_{MM}, D_{ML}, D_{LH}, D_{LM}, and D_{LL} are the self- and mutual-impedance voltage-drop constants of the network. These constants are obtained by considering unit load at the terminal indicated by the second subscript and determining the voltage drop measured from the source S to the terminal indicated by the first subscript.[2] Thus D_{HH}, D_{MM}, and D_{LL} are respectively the self-impedances of the transformer from terminal S to the terminals H, M, and L, respectively. The other symbols indicate the mutual voltage-drop constants.

The values of these voltage-drop constants in terms of the two-terminal impedances are as follows:

$$D_{HH} = Z_{SH} \quad (4)$$

$$D_{MM} = Z_{SM} \quad (5)$$

$$D_{LL} = Z_{SL} \quad (6)$$

$$D_{HM} = D_{MH} = \frac{Z_{SH} + Z_{SM} - Z_{HM}}{2} \quad (7)$$

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1. For all numbered references, see list at the end of the article.

$$D_{HL} = D_{LH} = \frac{Z_{SH} + Z_{SL} - Z_{HL}}{2} \quad (8)$$

$$D_{ML} = D_{LM} = \frac{Z_{SL} + Z_{SM} - Z_{LM}}{2} \quad (9)$$

The derivation of the formulas for the voltage-drop constants may now be considered. The values for D_{HH}, D_{MM}, and D_{LL} are obviously the self-impedances between

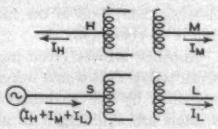

Figure 1. Schematic diagram of four-winding transformer two-terminal impedances Z_{SH}, Z_{SM}, Z_{SL}, Z_{HM}, Z_{HL}, and Z_{ML}

the source and terminals H, M, and L, respectively. For the determination of the mutual voltage-drop constants it is convenient to use an equivalent circuit such as Starr's form, as shown in figure 2. It is not necessary to determine the values of the branch impedances, a, b, c, d, e, and f, but merely to assume that the transformer may be represented in this manner. Remembering the definition of the voltage-drop constant as the impedance drop caused by unit current at the terminal indicated by the second subscript and determining the drop from the source S to the terminal indicated by the first subscript, one may write the following equations by inspection.

For unit load drawn from terminal H and supplied from S, the voltage drop from source to M is:

$$D_{HM} = D_{MH} = d + (e+f)\frac{f}{2(e+f)} = d + \frac{f}{2} \quad (10)$$

Similarly,

$$D_{HL} = D_{LH} = d + \frac{ef}{2(e+f)} \quad (11)$$

$$D_{ML} = D_{LM} = d + \frac{e}{2} \quad (12)$$

The values of $\left(d + \frac{f}{2}\right)$, $\left(d + \frac{ef}{2(e+f)}\right)$, and $\left(d + \frac{e}{2}\right)$ may be expressed in terms of the two-terminal impedances by the following method. The impedances between terminals of the equivalent network may be written by inspection and equated to the corresponding two-terminal impedances with the following results:

$$a + \frac{e(2f+e)}{2(e+f)} + b = Z_{MH} \quad (13)$$

$$a + \frac{e+f}{2} + c = Z_{HL} \quad (14)$$

$$a + \frac{f(2e+f)}{2(e+f)} + d = Z_{SH} \quad (15)$$

$$b + \frac{f(2e+f)}{2(e+f)} + c = Z_{ML} \quad (16)$$

$$b + \frac{e+f}{2} + d = Z_{SM} \quad (17)$$

$$c + \frac{e(2f+e)}{2(e+f)} + d = Z_{SL} \quad (18)$$

By solving for a from equation 15, b from equation 17, and c from equation 18, and substituting in the remaining equations:

$$d + \frac{f}{2} = \frac{Z_{SH} + Z_{SM} - Z_{HM}}{2} = D_{HM} \quad (19)$$

$$d + \frac{ef}{2(e+f)} = \frac{Z_{SH} + Z_{SL} - Z_{HL}}{2} = D_{HL} \quad (20)$$

$$d + \frac{e}{2} = \frac{Z_{SM} + Z_{SL} - Z_{LM}}{2} = D_{ML} \quad (21)$$

This verifies the relations given in equations 7 and 9.

Perhaps it should be pointed out that voltage-regulation

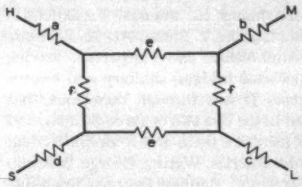

Figure 2. Equivalent circuit of four-winding transformer

problems are frequently stated in terms of kilovolt-amperes and power factor instead of load currents. For such cases the method just outlined may be used by adjusting the assumed currents in accordance with actual voltages at various terminals.

References

1. An Equivalent Circuit for the Four-Winding Transformer, F. M. Starr. *General Electric Review*, March 1933, pages 150–7.

2. Symmetrical Components, C. F. Wagner and R. D. Evans. McGraw-Hill Book Company, New York, N. Y., 1933, chapter 12.

Service Voltages for Lighting

THE General Electric Company's annual analysis of population reported as being served at various lighting voltages shows a continued shift toward 120 volts, with decreases in both the 115- and the 110-volt percentages. The percentage of population receiving lighting service at 125 and 130 volts is almost negligible (actually less than one-tenth of one per cent) and shows no sign of increasing. The trend is as shown in the following table.

Per Cent of United States Population in Areas Supplied at Different Voltages—100–130 Volt Range

Voltage	1923	1928	1933	1937	1938
110	36.3	15.9	5.2	1.8	1.4
115	40.9	61.6	61.7	52.1	49.5
120	19.4	22.4	33.0	46.0	49.0
All others	3.4	0.1	0.1	0.1	0.1
Total	100.0	100.0	100.0	100.0	100.0
Average voltage first three items only	114.1	115.3	116.4	117.2	117.4

Why So Few Famous Engineers Today?

IN A thought-provoking article published in the August 17, 1939, issue of *Engineering News Record*, Farley Gannett asks why so few engineers of today have obtained fame comparable to that of many engineers of past decades and puts forward several of the most plausible explanations that have been suggested to him. Excerpts from the article are given in the following paragraphs.

The deaths of Harrison P. Eddy, Hugh L. Cooper, and Guglielmo Marconi left notable vacancies in the fast dwindling ranks of the world's famous engineers. Within a decade Allen Hazen, General Goethals, Leonard Metcalf, Thomas Edison, James H. Fuertes, Frederick P. Stearns, Waldo Smith, Charles P. Steinmetz, M. I. Pupin, John R. Freeman, and others have departed, leaving monuments in waterworks, bridges, sanitary and electrical engineering works. It was through these men that engineering developed in the last two or three decades, and it was by reason of men like them and Rudolph Hering, Alfred Noble, the elder Fuertes, Waring, George Westinghouse, Desmond Fitzgerald, Barclay Parsons, Roebling, Eads, and others that engineering became an important and respected profession in the United States; their names became and have remained familiar and honored among members of their profession, some of them also to the general public.

A few engineers of note are still with us, such as Ralph Modjeski, John F. Stevens, John Hays Hammond, Herbert Hoover, and Arthur Morgan. We all know these men by reputation. There are not many that could be added to this list today. Ten years ago there were a score or more of names well known in engineering for years; only a few have made their reputations recently. The list of great ones has been steadily declining, and no recruits seem to be filling the depleting ranks.

There are many reasons why an engineer becomes well known; it may be ability, it may be luck, it may be character, it may be salesmanship or ambition or perseverance or any number of other things or a combination of several. Without some ability it would be hard to think of an engineer becoming famous, but a combination of ability and a decided character would be a great help. Add salesmanship or showmanship and a little luck and a lot of perseverance, and maybe there you have it, but there must be daring and courage because these make for human interest, and there is seldom fame without human interest.

Why were the men named above widely known? Why are their names and their deeds living after they are gone? Did these men achieve fame because they were among the ablest of engineers, or were some of them mediocre engineers who had something else that made them prominent among others, that caused them to be remembered and their names to become familiar to succeeding generations of engineers?

The consensus among men with whom I have talked seems to be that it requires a pioneer to make a name for himself, and they seem to think that the possibilities for pioneering in engineering have ceased. But have they? Will pioneering ever really cease? New developments, changes in old, involve pioneering. There are so many things being done on a far larger scale that it is hard to tell what is pioneering and what is not, but it is just as unfair to say that there is no more pioneering possible in engineering today and in the future as it would have been to say it 50 years ago.

Another answer given me was that much of the great work today that would otherwise make men famous is being done by the government and that names and individuals are submerged in government work. Nevertheless, there are hundreds and perhaps thousands of engineers in private practice today who are not doing government work and none are even projecting their heads above the horizon. Another suggestion is that engineers who are not working for the government are mostly working for corporations and that corporate employment eliminates the possibility of a man's making a name for himself. He may make his corporation famous, but not himself. Steinmetz worked for a great corporation and yet he achieved fame.

Another suggestion is that for every engineer graduated from engineering schools 50 years ago there are from 10 to 100 being graduated now; that it is harder to emerge from a large field than it is from a small one. Also, where competition is so strenuous as it is today and has been for 20 years, one gets much less opportunity for accomplishing great results.

The engineering profession is being used for greater things today than ever before in this or any other country's history. Why are not personalities being developed from these great works, why are not engineers being made famous thereby? This should be a time not only of greatness of our profession but for the individuals in it.

There is an old saying that you can't keep a good man down, and maybe that is what it is—that there aren't really good men developing in the profession today. And by a good man, I mean not only intelligent, educated, trained, and experienced, but I mean a man of character, energy, and, above all, enthusiasm and a certain amount of showmanship. Such a man should be able to rise from those around him to get above the surface and have his name resounding from the housetops whether he works for Uncle Sam, for a great corporation or for himself.

In an editorial commenting on this article the New York *Sun* on August 28, 1939, called attention to a statement made recently by President Harvey N. Davis of Stevens Institute of Technology to the effect that life in the 20th century has been profoundly changed by engineering, and that the social and economic significance of the profession will increase. "In short," the editorial concluded, "engineering itself may become more 'famous' than any of the great personalities in its past have made it." Perhaps some readers of ELECTRICAL ENGINEERING will be stimulated to reflection on this subject; contributions to the "Letters to the Editor" columns are invited.

Effects of Technology on Our Social Thinking

ROBERT W. KING
MEMBER AIEE

The many and varied successes in technology have inspired in the minds of millions unskilled in technological methods the belief that such methods are directly applicable to social problems. The engineer should be the first to recognize the danger in this misconception and should do what he can to educate and warn the lay public that principles applicable to his inanimate problems cannot be applied directly in the domain of social phenomena.

EMERSON said "To be great is to be misunderstood." Perhaps the time has come when engineering has attained to a degree of eminence that causes it to be misunderstood. I do not mean, of course, that it is misunderstood by those "skilled in the art," but rather by the great lay public. This nontechnical opinion does not take any derogatory form—rather, it is overflattering; and herein may lie certain dangers.

Technology in its applications has been so fruitful that it has certainly aroused the popular imagination. With what powers and potentialities the nontechnical mind in general clothes technology it is impossible to determine. But evidence is not lacking that in many respects people have come to expect more than can be delivered. Nature, in rewarding research efforts with so rapid a disclosure concerning the properties of materials, tends to distort the perspective of the layman. In bringing not only the comforts of life, but many of its luxuries as well, virtually within the reach of every one, the modern machine age has come so near realizing age-old dreams of plenty that mass patience breaks down even at the prospect of small delays in progress toward greater material welfare. An economic depression is not a new phenomenon. Nor was it so long ago that hard times meant not only misery but virtual starvation for multitudes. Today, even in depressions, our poorest classes are perhaps better off than were most of our forebears 200 years ago in times then considered prosperous.

As engineers we have quite properly emphasized the importance of efficiency—each improvement in our prime movers being measured in terms of thermal and mechanical efficiency—until the world generally has taken up the chant, demanding now that the affairs of state be subjected to the criterion of efficiency. The engineer should be the first to recognize that there is danger here of misusing a good idea. But, further, he should do what he can to educate and warn the lay public that principles applicable to his inanimate problems cannot safely be carried over, without careful scrutiny, to the domain of social phenomena. To be sure, there are such things as an efficient government, an efficient banking system, an efficient educational institution. But the definition of what we mean by the word "efficiency" when used in this sense is far more complex and difficult to state than the precise meaning we have in mind when we speak of the efficiency of a mechanical device. Among other things, we must temper our technological desire for efficiency with the justifiable demands of individual liberty. The mechanically efficient state is symbolized by the military type of organization. It has its uses, but I am sure it is not a satisfactory substitute for a democratic political structure. Our present democratic forms express many centuries of evolution and it is difficult to believe that we must now establish arbitrary and despotic forms of governmental administration in order to assimilate the benefits that are potential in technology.

Closely connected with the engineer's concept of efficiency is that of planning. No one would undertake to build a power house, a railroad, or a factory without a carefully worked-out plan. In the minds of millions unskilled in the methods of engineering, the engineer's success in planning his quantitative undertakings has inspired the belief that planning can be equally effective when applied to affairs of state. This belief might perhaps be classed as faith in the formula and in the machine. We expect an educational formula to make us wise and we expect a social machine to make us prosperous. National planning and planned economy are now popular catchwords. Why tolerate unbalance and maladjustment in matters involving national welfare when we have succeeded in eliminating them from the generating station and assembly line?

National Planning Leads to Dictatorship

This argument is appealing—insidiously so—particularly to those who are not overly familiar with the true nature of the engineer's work and who do not detect the fundamental differences between his problems and those of administration and government. In brief, the trouble is that the social state is a collection of diverse groups with individual interests and ambitions. We see in Europe some attempts to surmount this situation. Whether these European governments label themselves Fascist or Communist, the essence of their political creed is that the individual exists only for the state. This is frequently referred to as the beehive type of social structure. Under one condition, this sort of regimentation, if one likes it, will get him out of a lot of trouble by cutting a sort of Gordian knot. The one condition is that the leadership of the regimented state be infallible. But if we do not

Based upon an address contributed to the symposium on "The Social Significance of Engineering" held October 26, 1938, at Lehigh University, Bethlehem, Pa.

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like to have our lives entirely ordered for us, we must recognize at the outset that the business of planning, when once introduced into the affairs of state, permits of no moderation. It is not a mere matter of chance that the three planned economies of Europe are harsh dictatorships. It cannot be otherwise. To plan without having a dictator to enforce execution would be as idle as for the engineer to build his ships of cardboard and his transmission lines of string. Each and every national plan, no matter how wisely and beneficially conceived, is bound to curtail the activities of certain groups while it enlarges those of other groups. Spontaneous resistance of affected groups is therefore inevitable, and such resistance and refusal to co-operate, unless quelled, must frustrate attainment of the goal conceived in the plan.

National planning lands us, therefore, at one jump in the hands of dictatorship. History speaks very plainly on this point. National planning is not an idea characteristic alone of our day, although it may well be that the engineer's success has been the means of resuscitating into a present menace what for a century and a half has been regarded as discredited theory. Modern advocates are boosting for a system which earlier periods were greatly relieved to be rid of. Rigid governmental control characterized the industry of England in the days of mercantilism immediately preceding the advent of the industrial revolution. Nor was England unique. According to Eli F. Heckscher (see Walter Lippmann's "The Good Society") there was a tightly drawn system of regulations whereby Colbert, the minister of Louis XIV, sought in his day to codify industrial practices. For the period 1666 to 1730, the regulations relating to the textile industry alone ran to over 2,200 pages, and he estimates "that the economic measures taken in this connection cost the lives of some 16,000 persons, partly through executions and partly through armed affrays."

Before leaving this general subject of what we might call the indirect or inferential effects of technology upon our social thinking, I feel that one other aspect is deserving of emphasis. It is one that naturally appeals more strongly to those engineers who are engaged in industrial practices than to those who have followed the academic side. At the outset I mentioned the rapidity with which the scientist and the engineer have developed new comforts and conveniences, and that this may have given rise to impatience on the part of those who believe that, like technical improvements, social changes and benefits should come out of some laboratory for political invention more quickly than they do.

Technological Events Cast Their Shadows Before

But rapidity of development in technology is much more apparent than real. Only those who see behind the scenes realize how many years frequently go into the developmental stage of some apparently simple product. As an example, I might refer to the telephone handset which which you are all familiar. Superficially it consists simply of a handle to which is attached a telephone microphone at one end and a receiver at the other. Actually it took years to develop, and herein lies the explanation of why it was not introduced in the United States much earlier. American telephone engineers were not at all satisfied with the early European handset, and to have adopted it would have seriously degraded the standard of telephone transmission established in this country. The accusation was occasionally heard during those early years that telephone engineers were indifferent to the desires and convenience of the American public, but this was farthest from the case. As a matter of fact, even after laboratory studies and a long program of development, it was not until upward of a million handsets had been manufactured and had been in service for from one to three years that a final design could be drawn up which it was confidently known would stand up in everyday service. The early handsets for the most part long ago vanished from service, but as a trial installation they were invaluable.

This I mention as just a simple illustration of the fact that the sort of thing which seems to the outsider to occur quickly is, in reality, a process of painstakingly feeling one's way. It is a fact that every line of industry verifies. Most emphatically is it true that coming technological events cast their shadows before, and usually years before.

Social Changes Should Be Inaugurated Slowly

Now the moral, as regards our present discussion, will be apparent. Social changes, even more than industrial changes must be inaugurated slowly if they are not seriously to upset such balance as our social machine attains. Moreover, the problem of inaugurating changes is greatly complicated by the lack of any laboratory for research and any facilities for conducting trial installations under suitable controls. What would the engineer do in his own domain under such circumstances? He would deliberate, study carefully, and scrutinize very closely such chances for experimentation as do arise. And I suggest that this is the advice which the technological fraternity at every opportunity should bring to the attention of the lay public.

For my part I like to think of this analogy, and to those who are familiar with thermodynamics it may also appeal. In social reforms we ought to strive to bring about changes by a sort of infinitesimal process. This may sound a bit idealistic, but like the thermodynamic counterpart, it gives definite limits which our practical operations can approach. Consider this example: At the telephone laboratories new ideas are being turned out with no end of enthusiasm, and yet the telephone business as a whole is not pulled and hauled and periodically upheaved as a result of new discoveries and inventions. The process of assimilation takes place smoothly and quietly—in fact, it forms an excellent practical illustration of what in thermodynamics is called a reversible change, where the exchange is not of quantities of heat, but of new ideas and new methods for old.

In a large social group such an objective is manifestly difficult to attain. A system of checks and balances is vitally essential; and underlying it there must be a popular

understanding that social evolution, to be effective, cannot come about as the result of the rapid administration of charges of legislative dynamite which convulse the national organism. In such an educational program engineers might well lead the way since they, perhaps more than the members of any other profession, realize the practical importance of slow and balanced development.

Perhaps the economist has overworked the expression "in the long run." More likely, because of the element of impatience with which we are all endowed, we tend erroneously to conclude that he has overworked it. Certainly the practical politician proves generally to be in too much of a hurry, and his stock in trade is to play upon mass impatience. But quite apparently, as the fruits of technology enter more and more intimately into our lives, it becomes increasingly difficult to resist the urge to overaccelerate the tempo of political and sociological change.

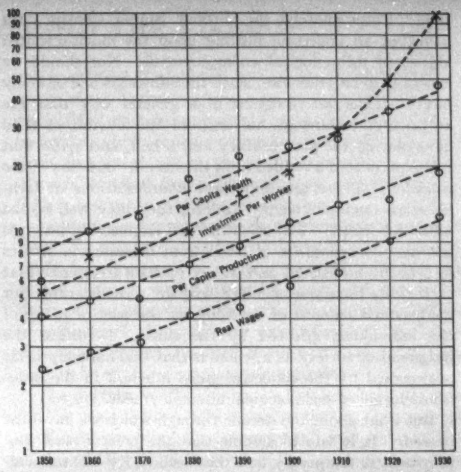
Real Wages Advance With Production

Granting, as we must, that the economist's "in the long run" makes his conclusions seem exasperatingly detached, it should be helpful to recall very briefly certain advances which the past 80 years of industrial history in the United States have seen accomplished. While searching recently for data capable of very condensed statement and yet basically significant, I chanced upon a combination that made an instant appeal to me. They do not tell a new or unsuspected story, but they do so definitely assert a relationship between progress in technology and progress in wage and living standards that I want to reproduce them.

In considering the accompanying figure, note first the curve which on an arbitrary scale (which is unimportant since the ordinates are logarithmic) indicates the growth of the per-capita wealth of the United States. In plotting this curve an attempt has been made to use a fixed unit in the measurement of wealth, thus eliminating fluctuations in price level. Over a period of 80 years, per-capita wealth with minor variations has shown a steady growth from the arbitrary value of 8 in 1850 up to more than 40 in 1930—roughly a fivefold increase. It would be beside the present point to argue the thesis that the fundamental source of this increase in per-capita wealth has been in the voluntary savings of the people.

Note next the curve indicating the growth of per-capita production over the same 80 years. We see that from the arbitrary value 4 it rises to about 20—again approximately a fivefold increase. In other words, over the period of 80 years, per-capita wealth and per-capita production have moved essentially in step.* (It should be recalled that on the logarithmic scale, equal differences between ordinates mean equal ratios between the quantities the ordinates represent.)

Now, as per-capita production has gone up, what has happened to wages? Of course, we are not interested in money wages or hourly rates of pay. We want to know



Statistics showing relationship between progress in technology and in wage and living standards

The data of this graph are for the United States. Figures for wealth and production are from Carl Snyder; those for real wages from "Income and Economic Progress" by H. G. Moulton; those for investment per worker from W. I. King

what has happened to yearly purchasing power. The answer is contained in the curve labeled "real wages." Beginning with an arbitrary value of 2.3 in 1850, real wages have mounted steadily to a value of 12 in 1930—again a fivefold increase. Not only, therefore, have real wages advanced as rapidly and *no more* rapidly than per-capita production, but both of these have advanced as rapidly and again *no more* rapidly than per-capita wealth.

While time will not permit a detailed discussion of the relationships suggested by the curves, I want to say that they leave with me the impression of being very fundamental. If over a period of 80 years—and we cannot say that these have been years unattended by intense labor agitation—we find that real wages have kept virtually perfect step with per-capita production, it suggests, does it not, that if we want to continue to increase real wages the very best way to proceed is to strive for further enlargement of per-capita production. In these curves we see renewed evidence that the basic interests of capital and labor are identical. Moreover, per-capita production and per-capita wealth are linked almost as the hen and the egg. To increase production brings with it the possibility of increasing savings and wealth; and only by increasing wealth, primarily in the form of improved capital goods, can production be augmented and real wages raised.

Problems of Instability

I wish that it were possible at this point to give a curve tracing the trend of employment over the same period of

* It may be noted that if we assume as constant the rate at which wealth makes production possible, and also as constant the fraction of each year's production which takes the form of capital goods representing an addition to wealth, the relation shown as having existed between wealth and production becomes a necessary one.

time. Unfortunately the United States Census data have but an uncertain bearing upon the much-disputed matter of technological unemployment. Nor should we expect it to be otherwise, since the subject is one of many facets. Thus we recognize in a general way that the advance of technology has reduced the amount of child labor during the past century and a half, and again that it has permitted a reduction in the number of hours in the workday. These are important manifestations of technological unemployment. Indeed, they may well be the most important! But scientific and engineering progress has also caused shifts of labor from declining industries to growing industries, and we are entitled to assume that such shifts have not occurred without a considerable but unmeasured amount of hardship on the part of many of the individuals affected by the shifts. Doubtless the judgment of society as a whole is that this hardship is far outweighed by the collective gains inherent in the beneficent forms of technological unemployment.

But what about the decade through which we have just passed? Is it safe to assume that the present slack employment is temporary and that technology has not suddenly and quite unwittingly brought the nation to a state of potential overproduction as regards many types of consumer goods? Considerable groups of people incline to the pessimistic view, and I shall not attempt to argue contrariwise, except to point out that the pessimists are forced to admit that the supposed condition of excess of productive capacity has come about quickly. This admission, by the nature of the case, weakens their contention. Social changes usually proceed slowly, and it is unlikely that public taste and obsolescence have been so quickly satiated in important respects.

To illustrate this point further, notice that the figure carries a fourth curve showing the change that has taken place in 80 years in factory investment per worker. From an arbitrary value of 5 in 1850 it rose to 100 in 1930, a 20-fold increase. In other words, factory investment has gone up four times as rapidly as wealth in general, and four times as fast as production. Nor is there reason to suppose that this trend has ceased. It seems inevitable that with the increasing complexity of industry the investment per worker must continue to rise. This fact points to several interesting conclusions, none more important I believe than this: that the growth in complexity of industry and the requirements for ever-increasing amounts of investment per person employed create a stabilizing influence. Technological unemployment, for instance, which is caused by the undermining of an old industry by a new, will become increasingly susceptible of control as larger amounts of capital are required to initiate and expand new industries. Outmoding of the old will continue, but at rates sufficiently retarded to mitigate the problems of readjustment. The importance of an adequate national savings program is also seen in a new light. As industry requires steadily increasing amounts of capital funds per worker to advance and expand, the necessity of augmenting our national wealth stands out in a new light—and the nonproductive consumption of wealth and of labor are matters for searching review.

In conclusion, let me repeat that I have introduced these curves, not so much to illustrate specific conclusions as to establish the fact that in the nature of things long periods of time must be at the bottom of most political-economic discussions and studies. Even the engineer, already accustomed to the long-term point of view, may need to school his patience; as for the lay public, such instruction is vital. Had we fixed our attention upon a 10-, a 20-, or even a 30-year period, the basic relationships existing between wealth, production, and wages would have been largely masked under the variation of other factors which because of the complicated nature of the problem could not be eliminated or compensated for with assurance. To appreciate this we have but to look at the 10-year values plotted in the figure and note how wide some of them fall of the straight lines which, taken together, they clearly determine. To neglect the long-term trend is likely, therefore, to lead to erroneous conclusions regarding the natural forces at work in society; and to misjudge these can result in as serious consequences as to be in error regarding the basic laws of physics and chemistry.

World Telephone Statistics

OF THE 37,098,084 telephones in service on January 1, 1937, approximately one-half, or 18,433,400, were in the United States, according to a survey recently compiled by the American Telephone and Telegraph Company. By continents, there were 19,952,423 in North America, 13,513,152 in Europe, 1,690,978 in Asia, 840,880 in Australia and other Pacific Islands, 765,435 in South America and 335,216 in Africa. Of the total number of telephones in use about 93 per cent could be reached by a subscriber in the Bell System. Private companies operated 22,538,753 or 61 per cent and government systems the remainder. There were 18,300,000 automatic or dial telephones. Two American cities, Washington, D. C., and San Francisco, Calif., lead the world's urban service with 37.43 and 37.00 telephones per 100 inhabitants, respectively, followed by Stockholm, Sweden, with 34.78 and Denver, Colo., with 30.96.

Countries	Number of Telephones	Per Cent of Total	Telephones per 100 Population	Number of Telephone Conversations
United States	18,433,400	49.69	14.39	26,800,000,000
Germany	3,431,074	9.25	5.08	2,562,000,000
Great Britain	2,791,507	7.53	5.93	2,000,000,000
France	1,481,788	4.00	3.51	941,000,000
Canada	1,266,228	3.41	11.48	2,449,102,000
Japan	1,197,129	3.23	1.70	4,772,000,000
Russia	950,000	2.56	0.55	
Sweden	687,566	1.85	10.97	1,000,000,000
Australia	562,868	1.52	8.31	514,000,000
Italy	560,660	1.51	1.31	
All others	5,735,774	15.45		
Total	37,098,084	100.00	1.71	

Electricity as an Industrial Fire Hazard

OF ALL FIRES in the United States and Canada during the years 1936 and 1937 (excluding those where lightning was the initial cause) 11.2 per cent were of electrical origin, and the loss was 10.9 per cent of all fire loss. These figures from the records of the National Fire Protection Association indicate that for all types of property, electricity ranked third as a cause of fire. The records of the Associated Factory Mutual Fire Insurance Companies on the same basis show that for industrial plants, electricity rates a strong first. For the years 1931 to 1938 inclusive, 19.8 per cent of the fires for which claims were made in Factory Mutual plants were caused by electricity, and the loss was 19.2 per cent of their total fire loss. That is, one out of every five fires was of electrical origin.

That the figures for industry should be greater than for the country as a whole is logical and easily explained. The average amount of electrical equipment in industrial plants is much larger than the average of such equipment in all classes of properties throughout the country, which includes dwellings, mercantile buildings, and many other kinds of structures. Every type of equipment made is found in industrial plants and the amount of this equipment and the size of individual pieces of apparatus is sometimes very large.

The following figures obtained from the Factory Mutual appraisal division give some idea of the proportional values of electrical equipments to the total insured values for several different kinds of modern manufacturing properties:

Type of Industry	Per Cent of Total Insured Value Represented by Electrical Equipment
Fully electrified newsprint mill	20.6
Up-to-date cotton mill	4.1
Hosiery mill	3.7
Lace-curtain mill	4.1
Average machine shop	2.8
Rubber product manufacturing plant	7.6
Large plant making electrical apparatus	12.0
Laundry	6.4

Of the various types of electrical equipment, wiring is responsible for 41.2 per cent of all the electrical fires; this includes all transmission, distribution, and branch circuit conductors in plant yards and buildings, all materials, devices, and fittings necessary for complete wiring systems, and lamp pendants with their drop wires, sockets, receptacles, attachment plugs, and the like. The resulting loss amounts to 66.4 per cent of all electrical-fire loss. The proportion of loss is exceptionally high, because fires of this class are more likely to spread and cause sprinklers to discharge water.

An additional 27.7 per cent of all fires of electrical origin start in motors. They cause 16.7 per cent of the electrical-fire loss. The reason the percentage of loss is less than the percentage of electrical fires is that usually these fires are confined to the machines and do not spread. Motor controllers, starters, and circuit breakers also are types of apparatus where trouble causing fires frequently originates. Such equipment causes about 16.6 per cent of Factory Mutual electrical fires. The loss they occasion is about 7.8 per cent of the total electrical-fire loss.

Lightning is the cause of an additional 5 per cent of claims for damaged electrical equipment made on Factory Mutual companies. In perhaps more than 90 per cent of the instances where industrial equipment has broken down during lightning storms, the lightning itself has not directly struck the equipment or conductors; the breakdowns are caused by high voltage resulting from the secondary effects accompanying lightning.

The average yearly number of fires of electrical origin for the years 1926 to 1930 inclusive, that is, the years immediately preceding the "depression," was 16.5 per cent of the number of all fires, while the loss caused by these fires was 17.6 per cent of the total fire loss. Comparing these percentages with the corresponding percentages for the years 1931 to 1938 inclusive, namely, 19.8 and 19.2 per cent, respectively, shows that the increase in number of electrical fires since 1931, or since the effects of the depression were felt, is 12.4 per cent. This increase has occurred during times when the electrical equipments generally were operating at reduced capacity and possibly some of them not at all. As electrical equipments have not been used as near their capacities since the start of the depression as before, when production generally was proceeding at high rates, it would naturally be expected that there would have been a reduction in the proportion of electrical fires and amount of loss experienced rather than an increase.

The answer to the question, "Why the increase?" is that since the start of the depression, the general level of quality of maintenance of electrical equipment has been very much lower than before. It is thought that at least one-third, and probably as many as one-half, of all fires originating in electrical equipment can be attributed to lack of care. Almost all manufacturing plants curtailed their maintenance efforts during the depression. Some did this to keep step with the lessened wear and tear, but many went further and cut down maintenance much more than was wise, undoubtedly with the thought that when business picked up again and the load on their equipments increased, they would give it more care and put it into good shape again before depreciation became excessive. However, many did not do it, with the result that breakdowns have occurred at an increased rate and the electrical loss has mounted.

Unless what appears to be a general let down in maintenance efforts is corrected, loss of property and production due to fires of electrical origin is likely to be serious in the future. The present low level of maintenance efforts should be raised and electrical equipments should be given the attention their importance warrants.

Abstracted from a paper by G. S. Lawler (A'11, M'13) chief electrical engineer, Associated Factory Mutual Fire Insurance Companies, Boston, Mass., presented at the Fire Service Extension School, West Virginia University, Morgantown, July 27, 1939.

Optimum Voltage for Airplanes

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NONMEMBER AIEE

Standardization of aircraft equipment is desirable when such standardization does not interfere with efficient operation. Equations developed for the standardization of electrical equipment indicate that the voltage for a large number of airplanes with d-c systems using storage batteries to carry peak loads can be standardized advantageously at 24 volts.

AIRPLANES are flying every day with even the major electrical units, such as generators, batteries, and motors, far heavier than necessary; but efforts to obtain ever higher airplane performance, together with the period of design refinements that follows in the wake of an initial "mushroom" development, are necessitating a review of past growth and the establishment of sound bases for future designs.

One extremely practical factor that must be kept in mind is standardization. This is particularly true of military airplanes, which cover the extreme range of types and sizes, and which also are called upon to operate from far-flung and isolated supply bases, where the maintenance of a multiplicity of replacement parts is not possible. The engineer, then, is forced to make a compromise between optimum design conditions for a particular application, and adherence to standard and available designs. However, it does not take much of a difference in weight to turn him toward the lighter, though nonstandard design.

Of the multitude of research problems involved in adapting complete electrical systems to a basis of minimum weight for a required job, the fundamental problem is that of power-supply-system characteristics. At present, d-c generators in parallel with lead-acid storage batteries provide an acceptable source of electric power in all but the largest airplanes.

The wiring installation of a military or transport airplane consists of insulated copper conductors of various sizes (number 20 to 00, American wire gauge) enclosed in thin-wall rigid or flexible aluminum conduit, with junction boxes and other fittings forming a complete metal-enclosed system. The remaining equipment, including generators, batteries, motors, lights, solenoids, radio transmitters and receivers, heating devices, and other units, usually is constructed according to fundamentally conventional designs and is used in all classes of airplanes.

Earlier types of airplanes carried little electrical equipment, and the use of 12 volts as standard was satisfactory. With increase in size and better performance in all classes of airplanes there was a considerable increase in weight of the electrical equipment and the determination of the optimum voltage, which is the voltage for which the weight of electrical equipment is a minimum, became more important. Calculations were made to determine the optimum voltage. These calculations were long and tedious since they required a calculation of the weight of the system for several voltages. The curve of weight versus voltage based on these calculations indicated that there was a voltage for which the weight was a minimum and that there was a considerable range of voltage over which the weight was very little more than the minimum. This range is referred to as the minimum region. In making these calculations certain assumptions had to be made as to the manner in which the weight of the component parts of the system changed with voltage. It was found that by making slight modifications in these assumptions they could be expressed in mathematical form. The analysis that follows shows how the equations used to express these assumptions lead to equations giving the optimum voltage and the minimum region in terms of certain constants associated with the weight of the electrical equipment.

Application is made of these equations to existing airplane electrical systems to show how their use facilitates the selection of the optimum voltage.

Development of Equations for Optimum Voltage

The following treatment of the effect of voltage on the weight of the system is developed after assuming that the weight of the component parts changes with voltage in the following manner:

1. The weights of generators and load equipment (motors, lights, etc.) are approximately independent of voltage.

2. The weight of a storage battery for a given watt-hour capacity is made up of a constant plus a quantity K_2E which is a direct function of the number of cells and hence indirectly a function of voltage, or

$$W_b = K_0 + K_2E \qquad (1)$$

3. The weight of cable and conduit is assumed to be related to the voltage as indicated under *A*, *B*, or *C*:

A(1). The weight of conductor varies inversely as the square of the voltage except that portion under 3*A*(3).
(2). The weight of conduit and insulation varies inversely as the voltage.
(3). A certain weight of cable and conduit is independent of the voltage.
B(1). The weight of conductor varies inversely as the square of the voltage.
(2). The weight of conduit and insulation varies inversely as the voltage.
C. The weight of cable and conduit varies inversely as the square of the voltage.

Within the voltage range considered safe for airplane operation the weight of generator and load equipment given under 1 is sufficiently correct for all practical purposes. For lights, switches, fuses, etc., the change in

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weight with voltage is small and in this voltage range the changes may be neglected.

In private communications to the authors C. B. Mirick of the Naval Research Laboratory and H. D. Wilson of the Auto-Lite Company have shown that to a close approximation the change in weight of storage batteries of a given type with voltage for a given watt-hour capacity may be represented by equation 1. Their calculations were made for voltages from 6 to 48 volts. In figure 1 are shown changes in weight of storage batteries with voltage for one-half-kilowatt and one-kilowatt output, for periods of 5 and 20 minutes, respectively. The data are based on batteries now in the service.

The range of K_2 for these batteries is from 0.6 to 0.85. In earlier types of aircraft batteries K_2 was found to lie between 1.35 and 1 pound per volt, for the outputs shown in figure 1. The latter value was used in several earlier calculations and some of the results are given here using $K_2 = 1$ instead of 0.85. The value of K_2 changes with the watt-hour capacity of the battery, but not with the voltage, and so may be regarded as a constant in subsequent differentiation with respect to voltage.

Assumption 3A(1) is strictly true if for each voltage the size of the conductor is selected so as to keep the percentage voltage drop constant.

Assumption 3A(2) states that the weight of conduit and insulation changes inversely with the voltage. A more exact equation would indicate the cross-sectional area of the insulation, and the conduit would change with the average radius multiplied by the thickness. Since the thickness of the insulation of the cable does not increase uniformly with the size, but with groups of sizes, an equation that would exactly express the relation between weight of insulation and size of cable is beyond the scope of this investigation. As will appear later little difference is obtained in optimum voltage whether this assumption or 3C is used.

Assumption 3A(3) is made because in many types of airplanes there are low-candlepower lights, indicating devices, etc., which require such small currents that mechanical strength limits the size of the conductor rather than electrical resistance.

Assumptions 3B are not as close an approximation to the actual relation between weights and voltage as 3A, and 3C is not as close as 3B.

The weights of the electrical equipment of any one airplane, according to assumptions 1, 2, and 3A, may be stated as follows:

Weight of generator, motors, etc.,

$$W_g = K_1 \tag{2}$$

Weight of batteries is given by equation 1.

Weight of conductor which is larger than the smallest allowable size and therefore changes inversely as the voltage squared

$$W_w = K_3/E^2 \tag{3}$$

Weight of conduit and insulation which changes inversely with voltage

$$W_c = K_4/E \tag{4}$$

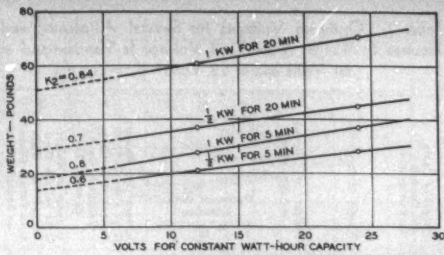


Figure 1. Curves for batteries showing change in weight with voltage for the outputs indicated, as computed from equation 1

Weight of cable and conduit which is of the smallest allowable size and therefore is independent of voltage

$$W_{wc} = K_5 \tag{5}$$

Adding, the total weight, W, may be written

$$W = K_1 + K_5 + K_2 + K_2E + \frac{K_3}{E^2} + \frac{K_4}{E} \tag{6}$$

Strictly speaking, K_5 is not a constant, but is a function of voltage, since if the voltage were very low, all the conductors might have to be larger than the smallest size having sufficient mechanical strength, while if the voltage were sufficiently high, a large proportion of the conductors might be of the smallest practicable size. However, as will be shown later large changes in the values of K_3 and K_4 within the range of reasonable designs, have little effect on the final result. If K_5 for any one airplane does change with voltage, most of the effect of the change is compensated by corresponding changes in K_3 and K_4.

Differentiating equation 6, putting the derivative equal to zero, and solving the resulting equation gives the voltage designated E_0. This is called the optimum voltage because it is the voltage for which the system has a minimum weight.

$$\frac{dW}{dE} = K_2 - \frac{2K_3}{E^3} - \frac{K_4}{E^2} = 0 \tag{7}$$

or

$$E_0(K_2E_0^2 - K_4) = 2K_3 \tag{8}$$

which gives the optimum voltage for assumption 3A.

If

$$W_{wc} = K_5 = 0 \tag{9}$$

equation 6 satisfies assumption 3B, providing W_w is the total weight of conductor and W_c the total weight of insulation and conduit. The optimum voltage is again given by equation 8 which is written

$$E_0(K_2E_0^2 - K_4') = 2K_3' \tag{10}$$

the constants K_3 and K_4 being written as K_3' and K_4' to distinguish the assumption under 3B.

If $W_{wc} = K_5 = 0$ and $K_4 = 0$, this means that the total weight of cable and conduit changes inversely with the

Table I. Optimum Voltages for Several Airplanes, and Increase in Weight (Pounds) if Voltage Is Standardized at 24 Volts and at 12 Volts; $K_3 = 1$

1	2	3	4	5	6	7	8
Weight of Cable and Conduit of 12-Volt System	Weight of Conductor	Weight of Conduit and Insulation	Optimum Volts, Equation			Increase in Weight if 24 Volts Is Used Instead of Optimum Voltage Given by Equation 11	Increase in Weight if 12 Volts Is Used Instead of Optimum Voltage Given by Equation 11
			11	10	8		
10	7	3	14	13	12.5	5	1
20	14	6	18	18	16	2	5
50	35	15	24	24	22.5	0	25
70	49	21	27	28	25	0	40
100	70	30	30	32	29	3	65
150	105	45	35	37	33	10	110
200	140	60	38	41	37	15	155
300	210	90	44	48	43	30	245
400	280	120	49	54	48	50	340
500	350	150	52.5	59	53	70	435

voltage squared. This is assumption $3C$, and equation 8 may be written

$$E_0 = \left(\frac{2K_3''}{K_2}\right)^{1/3} \tag{11}$$

Since W_w in equation 3 designates the total weight in accordance with assumption $3C$, the constant K_3 is designated by K_3''.

The constant K_1 which designates the weight of the generator, motors, etc., is of no importance in determining either the shape of the curve or the optimum voltage, and in the following computations is omitted. The weight of the system without the generator is designated W'. Equation 6 may then be written for the weight of battery, cable, and conduit according to assumptions $3A$, $3B$, and $3C$.

Assumption A:

$$W' = K_0 + K_2E + \frac{K_3}{E^3} + \frac{K_4}{E} + K_5 \tag{12}$$

Assumption B:

$$W' = K_0 + K_2E + \frac{K_3'}{E^3} + \frac{K_4'}{E} \tag{13}$$

Assumption C:

$$W' = K_0 + K_2E + \frac{K_3''}{E^3} \tag{14}$$

Computations

In table I are shown the results of computations for several airplanes which, if equipped with 12-volt systems, would require the combined weights of cable and conduit shown in the first column. Columns 2 and 3 show the weights of conductor and conduit and insulation, respectively, on the assumption that 70 per cent of the combined weight is that of the conductor. The optimum voltage for each airplane, as calculated from equation 11, appears in column 4. In these computations the battery constant K_2 is taken as 1 for all weights of cable and conduit. If it is assumed that the airplane with the greatest weight of cable and conduit requires the largest battery, then K_2, if it changes at all, probably will increase with increase in weight of cable and conduit. An inspection of the equations shows that with an increase in K_2 the optimum voltage will be decreased, and if K_2 increases with the size of the plane the optimum voltage for the heavier units will agree more nearly with that for the lighter units than is indicated by the values in table I. Using the single value $K_2 = 1$ for all weights of cable and conduit gives the maximum difference between the optimum voltages for the large and small units.

The other constant K_3'' appearing in equation 11 was calculated for each airplane from equation 3, using for W_w the combined weight of cable and conduit for a 12-volt system, since for the conditions under which $K_3 = K_3''$, the value of W_w is the combined weight of cable and conduit shown in the first column.

In column 5 are given the optimum voltages calculated from equation 10. The constants K_3' and K_4' were calculated for each airplane from equations 3 and 4, respectively, using for W_w the values from column 2, and for W_c those from column 3, since for the conditions under which $K_3 = K_3'$ and $K_4 = K_4'$, the value of $K_5 = 0$.

The optimum voltages in column 6 were calculated from equation 8, with the assumption that the part of the weight that is independent of voltage consists of 20 per cent of the weight of conductor and 30 per cent of the weight of insulation and conduit in the 12-volt system.

Table I indicates that although the assumptions leading to equations 8, 10, and 11 are different, the calculated optimum voltages are nearly the same.

Column 7 shows the increase in weight by adopting 24 volts instead of the optimum voltage computed from equation 11. Column 8 shows the increase in weight by adopting 12 volts instead of the optimum voltage. A decided saving in weight is indicated by adopting 24 volts instead of 12 volts.

Optimum Voltage for Five Airplanes

In columns 2, 3, and 4 of table II are given the total weights of cable and conduit, the weight of cable and the weight of conduit respectively, for five different types of airplanes. Since it is difficult to estimate the weight of insulation on the cable, the constant K_3' is obtained by using the weight of the cable as the weight of the conductor, and K_4' is calculated from the weight of the con-

Table II. Weight (Pounds) of Electrical System of Five Airplanes, and Increase in Weight if Voltage Is Standardized at 12 Volts and at 24 Volts

1	2	3	4	5	6	7	8	9
					Difference in Weight Between			
	Weight of Cable and Conduit for a 12-Volt System			Per Cent of Cable Weight to Total Weight	E_0 and 12 Volts, Equation		E_0 and 24 Volts, Equation	
Airplane*	Total Weight	Weight of Cable	Weight of Conduit		14	13	14	13
A	22.9	11.6	11.3	50.7	8	5	1	1
B	33.21	16.81	16.4	50.6	15	11	0	0
C	54.49	30.46	24.03	55.9	31	25	0	0
D	111.85	77.75	34.1	69.5	79	71.5	5.5	0.5
E	204.5	119	85.5	58.2	163	145	19	23

* Airplane A is a single-seat type, B a two-seat type, and C a three-seat type; D is a small twin-engine type, and E a large twin-engine type.

duit; K_3'' is based on the total weight given in column 2, using equation 3. Substituting these values in equations 10 and 11, with K_2 taken as 0.85, the optimum voltages are obtained. Columns 6 and 7 show the increase in weight if 12 volts is used instead of the optimum voltage. In columns 8 and 9 are given the increases in weight that would result from using 24 volts instead of the optimum voltage. The agreement between these two columns indicates that it is not important whether the optimum voltages are computed from equation 13 or 14 for the range of weights covered by these airplanes. The ten curves in figure 2 show the change in combined weight of battery, cable, and conduit with voltage using equations 13 and 14.

Discussion of Results

In determining the optimum voltage for a large number of airplanes, some of which are in use and some of which have not yet been designed, it was necessary to make broad but reasonable assumptions as to how the weight of electrical equipment will change with voltage. The calculations for this change in weight are based upon the assumptions 1, 2, and 3 given hereinbefore, that all generators, batteries, cables, and conduits have a voltage-weight relation that holds for all sizes of airplanes. The calculations may be said to apply to many classes of airplanes whose constants K_3', K_3'', and K_4' cover a range for which the ratio of the largest to the smallest value is 50 to 1.

The shape of the curves depends upon K_3, K_2, and K_4. The constant K_2 changes so slowly with a change in the size of the battery that it may be taken as a constant over a considerable range of battery sizes. Constants K_3 and K_4 depend upon the weight of the cable and conduit, and by using these as parameters a family of curves is obtained all of which have the same general shape. The optimum voltages are determined by the shape of the curves rather than their positions, and since the change in weight with voltage is slow in the neighborhood of the optimum voltage, the curves may be said to have a minimum region. It is because of this slow rate of change in weight with voltage that such good agreement is obtained for the wide range of values using the three diverse assumptions 3*A*, 3*B*, and 3*C*.

The assumption that the weight of the cable is 70 per cent of the total weight of cable and conduit was true for only one airplane as shown in column 5 of table II. However, as shown in figure 2, the curves plotted from equation 14 for the smaller weight of cable and conduit are almost identical with the curves plotted from equation 13, notwithstanding the difference in assumptions.

Referring to equation 11 it may be seen that the optimum voltage depends upon the weight of cable and conduit and the constant K_2. This constant for the two larger batteries for which curves are shown in figure 1 is for all practical purposes the same, since it changes less by doubling the capacity than the uncertainty of the other factors entering into this equation. This means that to a reasonable approximation the optimum voltage

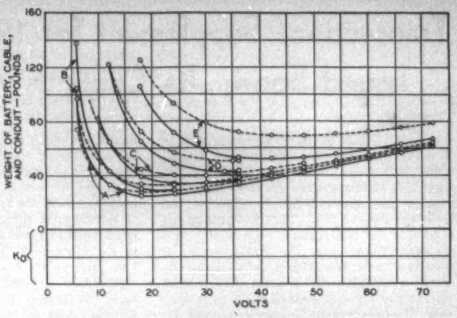


Figure 2. Curves showing change in weight of equipment with voltage for the five airplanes listed in table II

Curves with solid lines computed from equation 14, with dashed lines, from equation 13

is independent of the watt-hour capacity of the battery, which seems somewhat paradoxical. In practice, this means that once the optimum voltage is determined, the discharge rate and output of the battery may be changed without affecting the optimum voltage, notwithstanding that the total weight of the battery is changed by changing the output.

The increase in optimum voltage with a decrease in K_2 suggests that with more efficient batteries a higher operating voltage is desirable. A recalculation of the values using $K_2 = 0.85$ instead of 1, would indicate higher optimum voltages in columns 4, 5, and 6 of table I.

The values given in table II are for $K_2 = 0.85$ and indicate 24 volts is the optimum voltage for the single-engine type. For the twin-engine type the voltage should be higher, but if a single voltage is to be selected for all classes of planes 24 volts seems to place the additional weight in the larger planes, which ordinarily should be able to take care of it.

Conclusions

Stated briefly the equations indicate the following:

1. While the computed weight of the system will change, the shape of the curves will be approximately the same whether assumptions 1 and 2 are combined with 3*A*, 3*B*, or 3*C*, at least for the range of weights covered by table I. The curves may be used to select the optimum voltage that will give approximately the minimum total weight in each case. The capacity of the battery selected will affect the absolute weight of this system, but the optimum voltage should not be greatly changed.

2. For airplanes of the single-engine type, standardization on 24 volts seems to meet the requirements for a large number of airplanes. For airplanes having 10 pounds of cable and conduit or less, there may be an increase in weight of 5 pounds or more if one of the existing types of 24-volt batteries is used. If batteries having a smaller increase in weight with increasing number of cells are developed, the penalty for this choice of higher voltage will be less.

3. For large airplanes where auxiliary power plants are used, it may be desirable to supplement the standard 24-volt generator-battery system with a higher-voltage a-c or d-c system without battery.

Transactions Supplement for 1939 to Be Issued Soon; Its Contents Are Outlined Here

IN ADDITION to the 95 technical papers which together with their related discussions will have been preprinted in the monthly TRANSACTIONS sections of ELECTRICAL ENGINEERING by the close of the current calendar year, 28 others will be included in the 1939 annual volume of AIEE TRANSACTIONS. For the convenience of members and subscribers who desire to secure a complete file of these 28 technical papers and their related discussions, a special "TRANSACTIONS Supplement" will be published in December. This supplement together with the 12 issues of ELECTRICAL ENGINEERING for 1939 will provide in complete form *all* the technical papers and discussions published by the Institute during the year.

Advance orders are required because the number of copies to be printed will be determined by the demand. Therefore members should be on the alert for the order form which they will receive soon through the mails. This year's supplement contains 240 pages and will be paper bound similar to ELECTRICAL ENGINEERING; the price is 50¢ per copy.

To acquaint members with the content of this year's supplement, brief abstracts of the 28 papers to be included are given on this and the following pages.

Basic Sciences

CURRENT Distribution in a Rectangular Conductor, *John L. Daley* (*A'36*). The extensive use of rectangular conductors for large alternating currents has made the determination of their electrical characteristics a problem of practical importance. Although these conductors are usually used in groups and in special configurations, no solution other than that of direct measurement has been given even for the basic problem of the distribution of current in a single isolated conductor. The mechanical complications of the direct-measurement method are great, and the results obtained are necessarily an approximation. The current density inside a rectangular section may be determined analytically if the surface current density, comparatively easy to obtain, is known. The method is partly experimental and partly analytical.

TWO-PHASE Co-ordinates of a Three-Phase Circuit, *E. W. Kimbark* (*M'35*). In recent years there has been an increasing interest in the use of substituted variables in the analysis of unbalanced three-phase circuits and machines. The best known and most widely used method is that of symmetrical components, in which the actual currents and voltages of the three phases are replaced by the zero-sequence, positive-sequence, and negative-sequence currents and voltages, and the three-phase circuit by three single-phase circuits; another method is the use of direct-axis and quadrature-axis quantities which has facilitated the analysis of salient-pole synchronous machines. A new set of substituted variables, which may be found simpler to use than symmetrical components in the analysis of certain types of unbalanced three-phase circuits, is related both to symmetrical components and to the direct- and quadrature-axis quantities, but differs from either. The name "two-phase co-ordinates" is proposed because the three-phase circuit to be analyzed is replaced by an equivalent two-phase circuit and a single-phase circuit similar to the zero-sequence network. Probably the chief application of the new method is in the field of power distribution, with its single-phase loads, unsymmetrical transformer connections, untransposed lines, and mixtures of three-phase and two-phase circuits.

VALUES of the Bessel Functions ber x and bei x and Their Derivatives, *H. B. Dwight* (*F'26*). The functions ber x and bei x and their derivatives are used frequently in electrical-engineering problems connected with heavy conductors and with wires at radio frequencies. For instance, current distribution and resistance loss in a round conductor, or in a coreless induction furnace, are often computed by means of these functions. Tables now have been computed for values of x from zero to 20, at intervals of 0.1 to five significant figures.

EFFECT of Corona Discharge on Liquid Dielectrics, *Joseph Sticher* (*A'30*) *and D. E. F. Thomas* (*A'30*). The proper functioning of much electrical equipment depends on electrical insulating mediums, such as oils, under conditions known to include corona discharge. Pure liquid paraffin, various cable oils, and ten hydrocarbons of known-type molecular structure have been studied in a test cell, and several of their characteristics were found to be changed by corona discharge. The power factor of all samples increased with bombardment, while in most instances the d-c conductivity of bombarded samples was considerably lower than the a-c conductivity calculated from power-factor values. Application of d-c potential to bombarded decalin for extended periods showed a temporary decrease in power factor and conductivity. The material responsible for changes in power factor and conductivity was found to constitute an extremely small portion of the bombarded oil. Currents resulting from application of identical a-c bombardment voltages to the test cell and gas evolution under bombardment were widely different for the various oils, while in practically all cases an increase in viscosity resulted from the bombardment of the oils.

THE Generalized Solution for the Critical Conditions of the Ferroresonant Parallel Circuit, *William T. Thomson* (*A'37*). A generalized treatment for the critical conditions of the ferroresonant parallel circuit yields a number of interesting conclusions to supplement those found for the series circuit in a recent paper. Unlike the series circuit with its voltage-sensitive characteristics, the parallel circuit is known to be current sensitive in the critical region. The critical current is greatly dependent on the value of capacitive reactance used, and as in the series circuit, this current increases with a decrease of capacitive reactance. Although applications of the parallel circuit are rather limited compared to those of the series circuit, the constant-current characteristics of the parallel circuit may be in some places where it is necessary to maintain a constant voltage in spite of fluctuation in line voltage. This constant voltage may be obtained by placing a constant impedance in series with the parallel circuit tuned to the critical stable condition. A negative-slope characteristic of the parallel circuit may be utilized to advantage when applied to a resistance thermometer.

SUBHARMONICS in Circuits Containing Iron-Cored Inductors—II, *Irven Travis* (*A'32*). With the assumption that the reader is familiar with an earlier paper ("Subharmonics in Circuits Containing Iron-Cored Reactors," Irven Travis and C. N. Weygandt, AIEE TRANSACTIONS, volume 57, 1938) the production of subharmonic oscillations in a series circuit consisting of a capacitor and an iron-cored inductor is studied by the method of matching boundary conditions. The calculations are carried out by means of a new mechanical calculating device, and are verified by differential-analyzer solutions. A sufficient, but not necessary, criterion for stability is deduced. Some consideration is given to the effect of resistance in the circuit, its effect on stability being of greatest importance in the region of saturation. Good accuracy can be attained in the calculations by this method provided the circuit is such as to admit of certain idealizing assumptions and the oscillations are stable.

Communication

THE Role of the Ionosphere in Radio Wave Propagation, *J. H. Dellinger*. Radio waves are reflected and caused to travel great distances by the ionosphere, or ionized region in the upper atmosphere. The ionized condition does not increase uniformly as the air pressure decreases with altitude, and because of varying distribution of chemical composition of air with height, there are certain strata or layers in the air in which a maximum of ionization exists. Sky-wave transmission is determined by, and calculable from, the heights and ionization densities and other properties of the ionosphere layers. The maximum usable frequencies at any distance, for instance, are directly determinable from the virtual

heights and critical frequencies measured in vertical-incidence experiments. Optimum frequencies similarly may be estimated, though not as certainly as the maximum usable frequencies. The received intensities of the waves may be estimated to a certain extent from ionosphere data, but much more extensive data are needed for this purpose.

HARMONICS in the A-C Circuits of Grid-Controlled Rectifiers and Inverters, *R. D. Evans (M'26) and H. N. Muller, Jr. (A'37).* A well-known property of all rectifier- and inverter-type apparatus is the production of harmonic distortions in both the current and voltage wave shapes on both the supply and output circuits. A theoretical method has been developed for predetermining the magnitude of the harmonics in terms of the d-c load current, the commutating reactance, the rectifier transformer secondary voltage, and the amount of grid control. Harmonic voltages in the supply circuit may then be calculated from the harmonic currents and the supply-circuit reactances at the various harmonic frequencies. General curves facilitate the calculation of the harmonic currents for the range of conditions usually encountered; other curves aid in the determination of the product of the supply-circuit current and its own telephone influence factor. An empirical modification of the theoretical method may be applied to a-c circuits with nonlinear frequency-reactance characteristics, such as that of a rectifier provided with a-c filtering equipment. The inverter is treated in a manner similar to that used for the grid-controlled rectifier.

THE Submarine-Cable Plow, *C. S. Lawton.* Submarine cables may be damaged by fishing gear dragged along the ocean bottom, and in areas subject to such damage some cables have been buried in trenches to a depth of from one-half to two feet. The operation was performed by a nine-ton plow that dug a trench and placed the cable in it. The plow was designed to vary the depth of trench according to the resistance of the ground, in order to prevent excessive tensions in the towline—a chain with an ultimate strength of 63 tons. Means were provided for indicating on the towing ship the cable tension at the plow, depth of burial, condition of cable ahead of the plow (whether sinking to the bottom or being pulled down), and angle of the plow on the bottom. The plow was lowered and towed from the bow of the ship. Suitable gear had to be provided for handling the chain, and a procedure for trenching agreed upon. Service interruption was minimized by choosing a route parallel to the existing cable, laying a new section of cable in a trench, and splicing the new cable into the old.

THE Submarine-Cable Depthometer, *D. H. Nelson.* The problem of plowing submarine cables into the ocean bottom (described in "The Submarine-Cable Plow," by C. S. Lawton) requires a means of checking the depth of burial of the cable after the plowing operation has been completed. The actual depth in inches below the surface of the ground is given by a magnetic detecting and measuring device that utilizes the protective sheath of iron wires on the cable. The magnetic field arising from the magnetization of the cable sheath, together with the distortion created in the earth's magnetic field by the cable sheath, generates an electromotive force in detecting coils when these coils are moved in a substantially horizontal plane through such a field. By the use of two sets of coils mounted in a sled, the influence of speed and other factors is canceled. Amplifying and recording apparatus on the towing ship is connected to the sled by a pair of wires in the towing line; depth of the cable is determined from the record. Further use has been found for the depthometer in locating cables and in determining the relative positions of two or more cables in a particular locality, after which grappling operations for the desired cable may be conducted with comparative safety.

REMOTE-Control Toll Board, *Gilbert Sorber and Arthur Bessey Smith (F'22).* Essential operating facilities placed at the disposal of toll operators for the switching and completion of long-distance calls have, in a general sense, remained substantially unchanged since the early days of toll switching. As toll systems become more complex with the extension of the system and development of new services, there is a tendency toward the adoption of new switching methods even though these methods require the toll operator to give a greater amount of undivided attention to each call during the build-up period. Development of the remote-control toll board has made it possible to retain the advantages of these new methods of toll operation, and at the same time achieve a saving in time and labor. The remote-control toll board provides for connections from local subscribers to toll, toll to local subscribers, and toll to toll by means of electromechanical switches under the control of toll operators. The application of the board is not confined to operation with Strowger central offices, since by means of trunk groups and repeaters, the automatic switches will operate with varied types of central-office systems, whether manual, automatic, or a combination of both. Line equipment can be of the ring-down type, common-battery manual, or automatic with varied dialing methods.

Electric Welding

PREDETERMINATION of Temperatures in Resistance Welds, *Walter C. Johnson (A'35).* One of the most important variables in the resistance-welding process is the temperature obtained in the region of the weld. If this temperature is too low, the parts will not unite, and if it is too high, a burned weld will result. The physical complexity of this problem has made a satisfactory mathematical solution exceedingly difficult. By extension of a simple graphical method for solving transient heat-conduction problems, many mathematically complex conditions may be handled with ease and routine calculations become simple. The analysis applies particularly to the resistance welding of comparatively thin sheets held between electrodes of equal contact areas, and covers a large percentage of resistance welds. It evaluates the temperatures, temperature gradients, and rates of heating and cooling of a cylindrical portion of the work enclosed between the electrodes as functions of both time and position along the axis of this cylinder. By determination of these quantities and a knowledge of the welding characteristics of the material, current and time for a good weld may be predetermined.

POWER Supply for Single-Phase Resistance Welders, *R. H. Wright (M'27).* The increasing use of a-c contact welders in metal-fabricating plants imposes single-phase low-power-factor fluctuating loads on the power system. To eliminate voltage disturbances, motor generators have been installed to serve as phase converters supplying single-phase power. Common applications for single-phase welding generators are associated with butt, flash, spot, and seam welders, and tube welding machines.

Each type of welding may be served best by a certain combination of motor, flywheel, and voltage regulator. Generators for butt and flash welders may be driven satisfactorily by synchronous motors, using generator field forcing for flash welding. Induction motors may be most satisfactory for spot and seam welding, perhaps with some additional flywheel effect; synchronous motors and voltage regulators may be most satisfactory for tube welding. Experience gained from past installations provides a basis for the correct application of conversion equipment for future requirements.

Electrical Machinery

EQUIVALENT Circuit Impedance of Regulating Transformers, *J. E. Clem (F'38).* As systems grow in complexity and service standards grow higher, the need for more accurate determination of system characteristics increases. From time to time the question of how to handle the impedance introduced into the circuit by a regulating transformer has arisen. Regulating transformers are in effect autotransformers, but differ from them in that the series winding is on a separate core and receives its excitation from a section of the shunt winding. This difference introduces considerable complexity into the determination of the impedance introduced into the circuit. However, the equivalent circuit impedance of regulating transformers may readily be determined by general equations.

AN AUTOMATIC Voltage Regulator Without Moving Parts Employing Ferroresonance, *Palmer H. Craig (F'38).* A new automatic line-voltage regulator operates without tubes or moving parts of any kind, and can be used for loads up to 625 kva. The operation depends upon the use of ferroresonant networks, in which iron-core devices are operated on the knee of their saturation curve in such a manner that for a slight change of applied voltage across these reactors there will be a slight change of flux in their cores. Due to the portion of the characteristic curve on which they are

worked, this change of flux will change the apparent inductance of the coil, throwing it either into or out of resonance with the associated capacitor at the frequency of the impressed voltage. A copper-oxide rectifier in the network supplies current to the d-c saturating leg of a saturable-core reactor, whose a-c coils are placed in series with the primary of a booster transformer. The secondary of the booster transformer is in series with the line. The device is claimed to require no maintenance attention nor expense, and to be highly efficient, very accurate, and much faster in its response than previous line regulators.

RECENT Developments in Generator Voltage Regulation, *C. R. Hanna* (*M'39*), *K. A. Oplinger* (*M'39*), *and C. E. Valentine* (*A'27*). A new rheostatic type of voltage-regulator element consists of a control member, requiring very small force and movement, arranged to vary a resistor having a large number of steps. Several silver buttons are so mounted that they may be actuated in sequence by a driving member. Each button is carried on the free end of a flat leaf spring which normally rests against a block of insulating material. The leaves are clamped together with insulation between them, and only a small movement is necessary to close the gaps between all the buttons in sequence. Each spring is connected to a tap on the regulating resistance. The same principle may be extended for relays for increasing the power-handling capacity of regulators. A mathematical treatment gives the requirements for stability and adequate damping for several typical voltage-regulating systems. It is shown that with certain systems, theoretically perfect regulation and also high damping are possible.

RESONANT-Type Constant-Current Regulators, *Roland R. Miner* (*M'37*). A resonant network composed of linear impedances can be contrived to maintain a constant current in one element when energy is supplied at constant voltage. There are various forms that such a regulator may take, but the underlying principles are the same for all. The resonant regulator will perform quite differently under different circumstances, and a convenient, simple method of predicting the performance of a given regulator under various conditions is helpful to those applying the device. Resonant regulators are affected by variations in the supply voltage, and usually operate at the same power factor as the load. The input current is proportional to the load; hence both open-circuit and overload protection are provided by an overcurrent device in the supply circuit. The load circuit is usually not reactive, and in case of a break there is practically no arcing, although film cutouts and similar devices operate perfectly. The efficiency is similar to that of an ordinary transformer, except that for small regulators the maximum efficiency will be near one-third load instead of three-fourths load as it is in most transformers, making the resonant regulator especially adaptable to small regulators that do not fit exactly the load to be carried. The high efficiency at light load makes it desirable for circuits that operate part of the time at half load or less.

Instruments and Measurements

ALUMINUM-Nickel-Cobalt Brake Magnets for Watt-Hour Meters, *Stanley Green* (*M'34*). A new permanent-magnet material with such a high coercive force that design is affected radically has been applied to watt-hour meters, where it provides economies in space and weight. The new damping unit is different from the old in size, cross section, and shape, and consists of a single horseshoe-shaped magnet on one side of the disk with a soft-iron armature opposite. Adjustment of the magnitude of damping is made by forming the armature in three pieces and moving one of them with reference to the other two in order to vary the reluctance of the flux path through the armature. Permanency in the new design has been demonstrated by tests, and the unit can be made much more resistant to transient magnetic disturbances than the common form of chromium-steel damping magnet unit. The new magnet is formed by casting, and heat treated. Its material falls within the classification of corrosion-resistant alloys, and no protective coating is necessary.

AN AUTOMATIC A-C Potentiometer and Its Application to the Nondestructive Testing of Insulating Equipment, *George Keinath* (*M'37*). The importance of the measurement of dielectric loss for determining the quality of high-voltage equipment has been well known for a long time by the high-voltage-cable industry, and its measurement has been included in the international regulations for acceptance tests of cables. It was obvious that the same method could be used also for testing other high-voltage devices, such as transformers, bushings, insulators, and capacitors, but manual adjustment of the bridge takes too long a time for the usual high-voltage test, which requires about two minutes, to obtain the characteristic diagram of power factor versus voltage and time. An a-c potentiometer equipped with an entirely new element, the zero motor, which serves both as zero indicator and motor for adjusting the sliding contact, can be arranged to draw a continuous record of the desired relation. Two motors, contacts, and charts are used to accommodate both active and reactive components. Large deflections over the whole ten-inch width of the paper are accomplished in not more than two seconds. The continuous diagram enables the observer to see what is going on, and to stop the test before complete breakdown.

DEMAND-Meter Time Periods, *P. M. Lincoln* (*F'12*) *and R. R. Sprole* (*A'36*). The demand meter has been used for many years to measure the maximum demand of the load taken by any user of electric service, although the time period over which this demand is taken has never been standardized. Two time periods, 15 and 30 minutes, and two types of meters, one measuring the arithmetic average of the load over the specified time and another in which time appears as an exponential function, are used in practice. Indications of maximum demand will be different when using the two types of meters. The first type of meter tends to cause adoption of a short time period where loads of relatively short duration, such as welding, are concerned. The second type of meter automatically recognizes the time of load duration. Adoption of a uniform time period over which maximum demand is measured is urged, based on obtaining satisfactory agreement between the readings of the two types of meters, although the differing fundamental principles make it impossible that the two types should always indicate the same values.

ELECTRICAL Equipment Used in Reflection Seismograph Prospecting, *C. C. Nash* (*A'33*) *and C. C. Palmer*. In the present-day search for petroleum, the reflection seismograph is an important and powerful tool. The reflection prospecting method measures depths to subsurface strata by recording the travel time of reflected sound waves. The acoustic energy of the sound wave is converted into electrical energy by a pickup, amplified, filtered, and recorded. The equipment, which must be rugged and portable, provides automatic gain control in the amplifier, filtering to eliminate frequencies outside the reflection spectrum, and means of recording reflections from several points on the earth's surface, together with the necessary timing mechanism. The average number of records which may be obtained in a day is about 40. From these records the folding and faulting of the various strata are mapped, and likely traps for petroleum revealed. The depths in which the geophysicist is interested range from a few hundred to as much as 20,000 feet.

SENSITIVITY of the Four-Arm Bridge, *A. C. Seletzky and L. A. Zurcher* (*A'38*). The rapid increase in the use of a-c bridges for the measurement of electrical and non-electrical quantities makes desirable a critical analysis of the performance characteristics of various types of bridge structures. Selection of a particular type of bridge depends upon the requirements for sensitivity and accuracy, and the magnitude and characteristics of quantities to be measured. The unbalanced voltage appearing across the galvanometer terminals of any four-arm network can be treated as a function of the impedances of the arms in such a way as to show directly the effect of a slight change off the balance point for any of the bridge arms. Because of the wide application of amplifiers operating into null detectors, determination of sensitivity in connection with the open-circuit voltage across the galvanometer terminals has become of greater interest. A summary of sensitivity analyses of ten types of bridges shows their approach to either quadrature type or Wheatstone type for high or low values of Q.

Power Generation

MODERNIZATION of Switch-House Design, Consolidated Edison Company of New York, Inc., *A. M. de Bellis* (*M'33*). A program of modernization has been undertaken by the Consolidated Edison Company of New York, Inc., which serves a population of 8,000,000 in an area

of approximately 500 square miles. As a result of past experience and the advancement in the art since the various stations of the system were built, the major objective has been that of securing a greater sectionalization of the switching equipment than previously existed. Physical sectionalization has been improved by fire walls and fire doors; main busses have been sectionalized electrically, and the single-bus arrangement used in preference to the double bus which had been used more generally in the past. In one station extensive use has been made of metal-enclosed equipment, including a new type of factory-assembled metal-enclosed bus construction. Bus differential protection and high-speed relaying have been provided as additional means of localizing station faults, ventilating systems have been improved, and power-supply systems for station auxiliaries and for generator excitation have been sectionalized.

MODERNIZATION of Switch-House Design, *H. E. Strang (A'28) and W. M. Hanna (A'26).* Complete shutdown of an important generating station affects a great number of power users of all classes, and the damage can be very great physically, commercially, and politically. To improve the reliability of such a station, the possibility of the occurrence of a fault must be reduced to a minimum, the physical damage produced by a fault must be kept to a minimum, the spread of the fault must be prevented, and as far as possible an interruption of service to any consumer must be prevented. The problem involves the physical design of the apparatus and its parts, the electrical arrangement of the gear and of the system, auxiliary equipment to cure ailments if they do occur, and the co-ordination of all into one coherent whole. The modernization or construction of any large switch house should take into consideration not only the physical structure with a view to minimize faults but also system connections and auxiliary equipment with a view to prevent serious outages. Means are available to design the apparatus and system to meet successfully any set of conditions which may be encountered.

RECONSTRUCTION of Switching Facilities at Essex Generating Station, *D. W. Taylor (M'28).* Progress in protective devices by 1935 had outmoded much of the equipment of a large station of the Public Service Electric and Gas Company, and studies were started to determine the feasibility of applying modern protective schemes to the existing plant. The modernization studies were broadened to include a complete survey of the station's adaptability not only for certain immediate additions, but for future requirements. Extensive rebuilding of the 13-kv, 26-kv, and 132-kv switching facilities was necessary. In the reconstruction, no unique or unusual apparatus or design features were used. Rather, with part existing equipment, new commercially available apparatus, and refinements in standard designs of structures, a plan was developed which it is believed will provide a high order of reliability. Emphasis was placed on separation and segregation as a second line of defense to stop the spread of a conflagration.

MODERNIZATION of L Street Station Switch House, Boston Edison Company, *C. A. Corney (M'20) and W. W. Edson (M'25).* Because of increased generating capacity and the addition of station ties, the calculated short-circuit fault current far exceeded the ratings of many of the oil circuit breakers in a generating station built in 1898. Modernization or replacement of the breakers would have been quite expensive. The scheme adopted called for a synchronizing bus with reactors connected to each of four bus sections, but the arrangement of busses and breakers in the switch house prevented effective application of modern principles of segregation. The necessary additional space was gained by using an unoccupied floor of the existing switch house, where small headroom introduced serious problems. In this particular installation, the masonry-cell type of construction was adopted in preference to metal-clad equipment. Along with the construction of the new switch house, there has been a considerable modernization program progressing for the rest of the station.

Power Transmission and Distribution

EQUIVALENT Circuits of Transformers and Reactors to Switching Surges, *L. V. Bewley (M'37).* The calculation of switching surges caused by circuit-breaker operations requires that transformers, reactors, generators, and other apparatus be replaced by their equivalent circuits. To be of much practical use, these equivalent circuits must be simple, as well as reasonably exact. Circuits that will react to switching in essentially the same manner as the apparatus which they replace have been obtained on a theoretical basis for reactors and several types of transformers, and their behavior compared with test results.

REGULATING Transformers in Power-System Analysis, *J. E. Hobson (A'36) and W. A. Lewis (A'27).* In the analysis of power systems, it is customary to represent generators, transformers, and transmission lines by their equivalent circuits. The resulting circuit network is solved either by representation on a network calculator, from which the solution is read directly, or analytically by successive simplification of the network. In setting up the sequence networks of systems for analysis, the common procedure is to select some one circuit voltage as a base and transfer the impedances of the various circuit elements from their actual values to equivalent values on the base voltage selected. When regulating transformers of variable ratio are involved, this process becomes confusing and difficult to follow. A straightforward approach to the problem is permitted by equivalent circuits that are set up to include ideal transformers where necessary, so that the circuit used is the exact equivalent of the actual transformer in every important respect, and may be substituted for it without making any conversions in the impedances of the other circuit elements. Then, where simplification is possible, the ideal transformers may be shifted from one location to another, until in the final diagram they may be dropped altogether.

Diesel-Electric Locomotive for Pike's Peak Railway

A RACK-RAIL Diesel-electric locomotive, said to be the first of its kind, has been built by the General Electric Company for the Manitou and Pike's Peak Railway, replacing the tilted steam locomotives used on the cog railway since its completion in 1891. Instead of hauling its load, the locomotive pushes a 50-passenger car from Manitou, Colo., at 6,562 feet elevation, to the top of Pike's Peak, 14,109 feet above sea level. The average grade is 16 per cent; the steepest 25 per cent. The new locomotive can provide traction at the wheels as well as the rack rail, but not simultaneously. It has two axles, weighs 20 tons, and is powered by three generating units, each rated 160 horsepower at an elevation of 1,800 feet. One control station is provided, and the same standard electric-drive equipment as is used in the company's new Diesel-electric industrial locomotives.

News

Of Institute and Related Activities

Summary of Local Activities Reported by Sections Committee

SECTION activities were the subject of discussion at the recent summer convention conference of officers, delegates, and members, as reported in the August issue, pages 352–3. At that time a mimeographed booklet on Section activities was distributed to the Section delegates. The booklet, which summarizes the information accumulated by the Sections committee during the past few years, has been prepared by the committee as a means of acquainting new Section officers with the types of activities found most fruitful in various Sections. The material has been accumulated since 1937, when the Sections analyzed their aims and activities (see ELECTRICAL ENGINEERING, August 1937, page 1046; March 1938, page 134; August 1938, page 351; August 1939, pages 352–3).

The following abstract of the report on Section activities, which supplements the accompanying chart, has been prepared by Chairman H. H. Race of the Sections committee. The chart has been revised since it was presented at the conference.

1. AIMS AND OBJECTIVES

Our major aim or objective as set forth in our constitution is reaffirmed:

"The advancement of the theory and practice of electrical engineering and of the allied arts and sciences and the maintenance of a high professional standing among its members."

This was on its adoption and still is our expression of an all-time faith in a chosen work. It is the agreed-upon goal of our integrated thinking and acting and therefore the criterion by which we test our efforts.

The Sections agreed that in furthering this major objective we are also called upon continuously to recognize minor aims, which are used to guide us in conducting our daily affairs. A summary of the most frequently mentioned of these may be stated briefly as follows:

"To provide opportunities for students and workers in the engineering field to become acquainted, to exchange ideas, to keep up to date technically, and to stimulate group activities."

Another type of minor aim, expressed in many ways, and apparently not yet clearly and definitely developed, has to do with the relation of the Section to the social group of which it is a part. Almost every Section analysis included some comment indicating interest in this question. Expressed variously it ran:

"To inform the public"; "to promote civic interest"; "to discuss economics"; "to co-operate in promoting education"; "to stimulate the activity of engineers in community and civic interests"; and so on.

Here we note a real desire on the part of our membership to carry over into social affairs in general some of the effectiveness which has marked our activities in technical fields.

Principally through such groups as the American Engineering Council and the Engineers' Council for Professional Development, the AIEE finds at least partial facilities for maintaining contacts in general social problems. For the local Sections, however, only very limited facilities are available through which can be worked out an engineers' analysis of local, social, or civic problems for the guidance of the group as a whole or its individual members. This gives rise to our second minor aim or social objective and here it would seem that our local Section experience provides us with

AIEE SECTION ACTIVITIES

| | 67 SECTIONS | AKRON | ALBANY | BALTIMORE * | BOSTON | CENTRAL INDIANA | CHICAGO | CINCINNATI | CLEVELAND | COLUMBUS | CONNECTICUT | DALLAS | DENVER | EAST TENNESSEE | ERIE | FORT WAYNE | GEORGIA | HOUSTON | IOWA | KANSAS CITY | LEHIGH VALLEY | LOS ANGELES | LOUISVILLE | LYNN | MADISON | MANSFIELD | MEMPHIS | MIAMI | MICHIGAN | MILWAUKEE | MINNESOTA | MONTANA | MUSCLE SHOALS | NEBRASKA | NEW ORLEANS | NEW YORK | NIAGARA FRONTIER | NORTH CAROLINA | OKLAHOMA CITY | PHILADELPHIA | PITTSBURGH | PITTSFIELD | PORTLAND | PROVIDENCE | ROCHESTER | SAGINAW VALLEY | SAN ANTONIO | SAN DIEGO | SAN FRANCISCO | SCHENECTADY | SEATTLE | SHARON | SPRINGFIELD | SYRACUSE | TOLEDO | TORONTO | UTICA | UTAH | VANCOUVER | VIRGINIA | WASHINGTON | WICHITA | WORCESTER | PER CENT PARTICIPATION |
|---|---|---

little guidance. However, this problem is quite likely the outstanding one of our time.

"We are not at loss as to our objectives in connection with it. We want to *preserve, protect, regain,* and *build* a social environment which will permit us to work for the advancement of the theory and practice of electrical engineering and of the allied arts and sciences and the maintenance of a high professional standard among our members."

Many local Sections want to do something about this. Insofar as such activities are constructive, this work is well within the scope of our objectives. In bringing to social problems the engineer's way of thinking, three aims are realized. First, these problems invariably have technical phases which lend themselves to correct solutions only through objective treatment. To this extent, therefore, science is advanced. Second, a high professional standard among engineers is realized only when co-operation and not isolation is the program. Third, the privilege of pursuance of our major objective requires a vigilant attitude toward the changing social structure, lest we find ourselves within an environment which considers our activities and aims unimportant.

2. ACTIVITIES

The accompanying chart summarizes the results of the surveys conducted during the past three years. The activities of the different Sections are extremely varied because of great differences in their size, location, and personnel.

The technical activities of most Sections are well organized. However, in addition, where they are not already doing so, the Section officers are urged to enlarge the scope of their activities in the following ways:

A. Take an active interest in young men before and immediately after they enter the profession: (*a*) through educational activities in secondary schools, (*b*) by sponsoring joint meetings with neighboring Branches, (*c*) by scheduling younger member and inter-Section prize-paper contests, and (*d*) by encouraging active participation in the Sections committee work.

B. Implement the engineer's desire for group activity in influencing social conditions: (*a*) by co-operation with other local engineering societies, (*b*) by approving or suggesting improvements in the AIEE model registration law (see page 354 of the August issue), (*c*) by continuously keeping informed regarding proposed legislation likely to affect electrical engineers, (*d*) by stimulating and organizing social and economic studies and discussions in local groups and by exerting influence in local affairs where engineering analysis can be advantageously employed, and (*e*) by expressing the engineer's reactions to national social and economic problems to and through the American Engineering Council.

Membership—

Mr. Institute Member:

"A substantial increase in the representation of each locality in the Institute" is the objective of the membership committee in its plans for the 1939–40 season. As in earlier years, the committee is counting upon the assistance of the individual member through the proposal of names of desirable candidates for admission; a communication on this subject will be issued shortly to the entire membership.

Qualified new members are essential to the health and growth of the Institute. Your prompt co-operation will be both helpful and highly appreciated.

L. L. Webb

Chairman, National Membership Committee

Charles F. Scott Honored by Connecticut Section

In consideration of "the accomplishments to his credit in the engineering field and his services to countless engineering organizations and the humanities," the AIEE Connecticut Section held a testimonial dinner for Doctor Charles F. Scott, September 19, 1939, on the occasion of his seventy-fifth birthday anniversary. The gathering was held at the New Haven Lawn Club, close by Yale University where Doctor Scott's name has been a byword since 1911. Some 150-odd were present to pay homage to the fifteenth president of the AIEE, many from points far outside the state.

Toastmaster was Past-President Frank B. Jewett who characterized Doctor Scott as one who more than any other single individual had constructively influenced American engineering during the past quarter-century. Speakers included President Farmer and Past-Director C. E. Stephens of the AIEE, President-Emeritus Angell of Yale University, and Former-Governor Cross of Connecticut. Presiding at the dinner meeting was Chairman R. S. Judd, and heading the general committee was Past-Chairman R. G. Warner, both of the Connecticut Section.

NRC Insulation Conference to Meet in Cambridge, Mass.

The twelfth annual meeting of the conference on electrical insulation of the division of engineering and industrial research, National Research Council, will be held at Harvard University, Cambridge, Mass., November 2–4, 1939.

According to the tentative program, the first day will be devoted to chemistry, physics, and measurements, and the second to properties of dielectrics, including insulation of high-voltage cables. The program for the third day has not yet been finally determined. The tentative program is expected to include about 25 papers. Presentation of papers will be brief, to allow for adequate discussion.

The conference will continue its usual practice of having presented unpublished researches and progress reports. The only record of the meeting will be a series of short abstracts of the papers presented, although it is expected that most of the material offered will eventually appear in finished form in various scientific and engineering publications.

Because of recent illness, Doctor J. B. Whitehead (A'00, F'12) of Johns Hopkins University, chairman of the conference throughout most of its history, has resigned that post. His successor has not yet been appointed. In the interim, arrangements for the coming meeting are being made by W. A. Del Mar (A'06, F'20) Habirshaw Cable and Wire division, Phelps Dodge Copper Products Corporation, vice-chairman; W. F. Davidson (A'14, F'26) Consolidated Edison Company of New York, Inc., secretary; and C. L. Dawes (A'12, F'35) electrical-engineering department, Harvard University, who is representing the University and arranging the social aspects of the conference, as well as visits to laboratories.

Temperature Symposium to Be Held in New York

A symposium on the measurement and control of temperature in science and industry will be held in New York, N. Y., November 2 to 4, 1939, by the American Institute of Physics, with the co-operation of the National Bureau of Standards, the National

Future AIEE Meetings

Middle Eastern District Meeting
Scranton, Pa., October 11–13, 1939

Winter Convention
New York, N. Y., January 22–26, 1940

Summer Convention
Swampscott, Mass., June 24–28, 1940

Pacific Coast Convention
Place and date to be announced.

Research Council, and officers and committees of many technical societies. Preliminary announcement of the meeting appeared in the April issue, page 180.

The program is in charge of representative committees of authorities in various fields, who have arranged for 100 or more papers on scientific and technical subjects, to be presented in concurrent sessions of selected groups. All interested persons active in science or engineering are cordially invited to attend the sessions, and take part in the discussions of papers. A complete program containing full abstracts of the papers to be presented will be mailed in advance on request to the Institute. It is suggested that those who expect to attend will inform the Institute (175 Fifth Avenue, New York, N. Y.) and make their hotel reservations early. Registration fee will be $1.00.

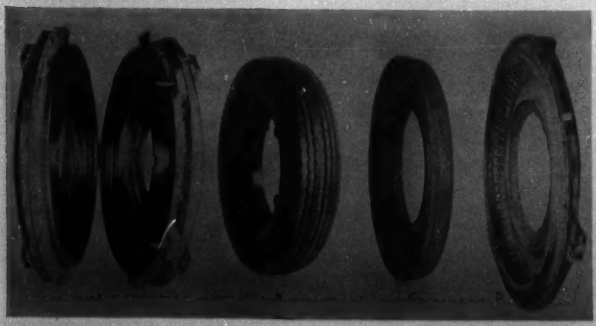
World's Largest Hydro Plant Now at Boulder Dam

The power plant operating at Boulder Dam is now the largest of its kind, since its seventh large generator has gone into steady operation, according to *The Reclamation Era* (August, 1938, page 193). The seven large units and one smaller unit give the plant a capacity of 860,000 horsepower. The Dnieprostroy plant in Russia, previously the largest hydroelectric power plant has a capacity of 746,000 horsepower.

The ultimate capacity of the Boulder Dam plant is 1,835,000 horsepower. It will eventually house 15 large generators, rated at 82,500 kva each, and 2 small ones, rated at 40,000 kva each. Another large generator is expected to be ready to go into steady service about October 1, and two more are now being manufactured. The generator most recently placed in operation was hurried to completion to prevent a prospective power shortage in the system of the Southern California Edison Company, which it serves.

Molds Produced by Electroforming With Iron

IN A series of demonstration lectures before groups of technical and trade publication editors, the United States Rubber Company recently described its "Ekko" process for the preparation of molds and dies by electroforming iron against a pattern. Electroforming is essentially a long-time electroplating process in which deposits up to one-half-inch thick are produced when heavy electroformed deposits of iron are separated from the underlying pattern, a cavity or die insert is obtained which has reproduced the shape and surface finish of the pattern in every detail. When properly mounted, this cavity or die may be used to mold or stamp objects that are exact duplicates of the original pattern. Although developed originally for producing automobile-tire molds, the process is now being used in the making of dies and molds for the plastics, glass, embossing, and metal stamping industries. The accompanying illustration shows: (*A*) A mold made by the usual process of engraving in which the tread design and cavity are cut out of a steel forging with special engraving machines; (*B*) rubber tire pattern ready for duplication by the Ekko process; (*C*) half of the resulting electroformed mold; and (*D*) electroformed mold fitted into "the watch case" back. The cross sectional close-up view shows how the metal is deposited into the pattern and the roughness that is characteristic of heavy electro deposits. A heated electrolyte is used in the process, and a period of 21 days is required to produce a complete tire mold. The iron produced by this process is said to be 99.98 per cent pure and substantially free from porosity; it is also about 50 per cent harder than cold rolled steel and has a heat conductivity nearly twice that of cast iron or steel.



Public-Utility Accident Rates for 1938

The National Safety Council's annual statistical report on accident rates in public-utility companies during 1938 shows 11.37 injuries per million man-hours of exposure and 1.97 days lost per thousand man-hours of exposure. The first, or frequency rate, is 16 per cent lower than in 1937, and the second, or severity rate, 1 per cent lower. The average frequency rate for all industries is 12.18; the average severity rate 1.53.

While large organizations within the industry had lower injury rates, the showing of small companies improved more over 1937 than did the average for the industry. Telephone and telegraph companies continued, as in the past, to have the lowest injury rates, averaging 4.40 for frequency and 0.14 for severity during 1938; these companies also showed the largest decrease in frequency since 1937, 21 per cent. Manufactured-gas companies made the largest decrease in severity, 40 per cent.

The commonest accident cause, reported in 119 fatalities and permanent partial disabilities was unnecessary exposure to danger. Accidents resulted from entering areas rendered unsafe by electrical or other haz-

Exposition Illumination Reprints Available

A small supply of pamphlets containing the 16-page special article published in the June 1939 issue of ELECTRICAL ENGINEERING on the remarkably effective decorative illumination characterizing the San Francisco-Golden Gate International Exposition is now available to members and subscribers at the special price of 25¢ each postpaid. The pamphlet, 16 pages and cover $8\frac{1}{2}$ by 11 inches in size, is printed on the same heavy special stock that was used in the June issue and includes all of the large and remarkably true-to-life four-color illustrations, together with the explanatory text and supplementary diagrams of equipment installation. Within the limits of available stock, orders will be filled in the order of their receipt.

Orders, together with 25¢ in cash or stamps, should be sent to AIEE Order Department, 33 West 39th Street, New York, N. Y., with sender's name and mailing address typewritten or printed in the interest of satisfactory delivery.

ards, standing under suspended loads, working on high-voltage conductors from above instead of from below, and gripping, holding, or lifting objects improperly. Chief mechanical cause was improper guarding.

The 1938 experience of the public-utility industry was compiled from reports of 625 companies whose employees worked 699,135,000 man-hours during the year. Of 30 major industries surveyed, public utilities ranked 16th in frequency of accidents, and 24th in severity. Since 1926, public utilities have decreased frequency rates 79 per cent, compared with a 68-per cent reduction for all industries, and severity rates 65 per cent, compared with 44 per cent.

National Safety Council reports on accident rates, which are issued for 24 industries and industry groups, are based chiefly on the records of members of the Council, although nonmembers are included in some cases. Information is compiled in accordance with standard definitions, and reports are identified by key numbers known only to the Council and the individual company.

Bakelite Corp. Bought by Union Carbide and Carbon

A further significant step in the trend toward integration in the plastics industry was taken August 29 when the Union Carbide and Carbon Corporation acquired all the assets of the Bakelite Corporation.

In commenting on this deal, *Business Week* indicates the significance of this move to the plastics industry by recalling the consolidations that began in the steel industry in the 90's and more recently in the automotive industry, with the emergence of the so-called "big three." Union Carbide previously had been supplying Bakelite with a large share of basic chemicals and materials, and the combined facilities seem to bring Union Carbide to the front along with Du Pont and Monsanto as the "big three" in plastics. New alignments are expected among the several competitive suppliers of plastic materials, which include General Electric and Westinghouse.

Chemical Exposition. The 17th Exposition of Chemical Industries will be held at Grand Central Palace, New York, N. Y., December 4–9. Exhibits will feature unit processes of chemical engineering, as well as equipment and product developments in industries which are chemical in nature, or chemically influenced or controlled. The student course in chemical engineering which has been a part of previous expositions will be offered again this year. Founded in 1915, the Exposition is now established on a biennial basis.

Principles of Naval Architecture. The Society of Naval Architects and Marine Engineers has announced the publication of a two-volume reference work, "Principles of Naval Architecture," intended to meet the need for a comprehensive modern text for students, naval architects, and marine engineers, as well as executives and others interested in the operation and maintenance of vessels. Written by a group of authorities, the two volumes were supervised by a control committee of the Society. Copies may be obtained from the Society of Naval Architects and Marine Engineers, 29 West 39th Street, New York, N. Y.; price $11 for the set.

American Engineering Council

War Plans to Be Studied By Civilian Board

With the approval of President Roosevelt, the Army and Navy have formed a War Resources Board, composed of six civilians prominent in industrial life, who will immediately review the comprehensive plans prepared over a period of years by the military authorities for the mobilization of industrial supplies in case of war.

Named to the new Board were Edward R. Stettinius, Jr., president of the United States Steel Corporation; Doctor Karl T. Compton (F'31), president, Massachusetts Institute of Technology; Walter S. Gifford (A'16), president, American Telephone and Telegraph Company; Dr. Harold G. Moulton, president, The Brookings Institution; John Lee Pratt, General Motors Corporation; and General Robert E. Wood, Sears, Roebuck and Company.

Immediately after the appointments were announced the Board convened in Washington to begin its work, and several meetings were held to acquaint the members with all details of present plans for industrial mobilization. After giving these thorough consideration it is expected that the Board will submit a report making suggestions, if necessary, for further refinements.

Experience from the Council of National Defense, headed by Walter S. Gifford in 1917, is available to the new board through his membership. It is assumed that the War Industries' Board, now an advisory arm of the Army and Navy Munitions Board, in the event of war would become a War Resources Administration reporting directly to the President. Presumably, it would attempt to co-ordinate the economy of the country with particular attention to the munitions requirements of the Army services and should war come, it would be assumed that these requirements for munitions would be co-ordinated with the needs of the civilian population.

Information at the office of the War Resources Board indicates that should a wartime industrial mobilization be necessary, it would revolve around the War Resources Administration, but that the actual administration of various activities would be in the hands of the regular agencies handling them or with new agencies.

Effective instrumentalities developed in the twenty-two years that have passed since the last war are the trade and technical associations. Practically all the industries are highly organized and are in possession of statistical and other information which can be quickly put at the disposition of a War Resources Administration.

Future Meetings of Other Societies

American Institute of Physics. Temperature symposium, November 2–4, New York, N. Y.

American Physical Society. 230th meeting, December 1–2, Chicago, Ill.
231st meeting, December.

Annual meeting (232d), December 28–30, Columbus, Ohio.

American Society of Heating and Ventilating Engineers. 46th annual meeting, January, 1940, Cleveland, Ohio.

American Society of Mechanical Engineers. Annual meeting, December 4–8, Philadelphia, Pa.

Conference on Electrical Insulation (National Research Council). November 2–3, Cambridge, Mass.

Institute of Radio Engineers. Fall meeting, November 13–15, Rochester, N. Y.

National Electrical Manufacturers Association. October 23–27, Chicago, Ill.

National Safety Council. October 16–20, Atlantic City, N. J.

Société Française des Électriciens. Television meeting, November, Paris, France.

Standards

Co-ordinating Committee 3 Announces Projects

When the AIEE standards committee organized sub-groups for special work (see May issue, pages 222–3) co-ordinating committee 3 was assigned the problem of reviewing the subject of insulation testing in electrical machines and the co-ordination of investigations of new tests for the evaluation of insulation in service.

The personnel of committee 3 is to be made up of engineers primarily interested in insulation. To date the following have accepted membership:

C. F. Hill, Westinghouse Electric & Manufacturing Company, *chairman*
J. S. Askey, Westinghouse Electric & Manufacturing Company
W. B. Kouwenhoven, Johns Hopkins University
S. H. Mortensen, Allis-Chalmers Manufacturing Company
H. R. Stewart, New England Power Service Company
J. B. Swering, Hartford Steam Boiler Inspection and Insurance Company
R. L. Webb, Consolidated Edison Company of New York, Inc.
R. W. Wieseman, General Electric Company

A review of present standards seems desirable at this time to determine if they are consistent with experience and developments since their adoption some years ago. Test procedures in foreign countries will also be reviewed and compared with American practice.

A second project recognizes the efforts of the users of electrical machinery to evaluate insulation in service and proposes to co-ordinate the efforts of other interested engi-

neering groups toward a more general solution of this problem, with final standardization, if possible.

Session on Standards at Scranton Meeting

In continuation of the symposium on rating held at the AIEE winter convention last January, a further discussion of rating and associated standards problems will be held on October 11, during the Middle Eastern District Meeting, Scranton, Pa., under the auspices of co-ordinating committee 4 of the standards committee.

Four papers will be presented. One of these will deal with the effect of solar radiation on temperature rise of apparatus, and another with the operating conditions affecting electrical apparatus met with in the steel industry. These two papers supplement the paper on weather conditions affecting electrical apparatus presented at the San Francisco convention, placing on record a general review of the ambient temperature and air conditions under which electrical apparatus operates.

The two other papers will deal with the rating and application of d-c motors and of distribution transformers, respectively, under conditions of variable load cycles. These papers point out design factors and insulation requirements which affect the selection of apparatus for use under variable load conditions, and supplement the similar information presented on induction motors at the January symposium.

Following the presentation of these four papers, an informal report will be presented by co-ordinating committee 4, which has been charged with the responsibility of revising AIEE Standard No. 1, dealing with the "General Principles Upon Which Temperature Limits Are Based in the Rating of Electrical Machinery and Apparatus." A meeting of this committee will be held in the morning preceding the technical session, and it is hoped that at that time reasonably complete agreement will be reached on a draft revision of this standard. An open discussion of this and other standards activities will be held following the presentation of the informal committee report.

The purpose of undertaking this revision of the AIEE Standard No. 1, which has not been changed since 1925, is to take into account the numerous changes in the various standards for specific types of apparatus which have been made since that time, and to assure a continuing sound basis for the further development of the American system of electrical-apparatus rating.

Standard No. 1 deals with the general considerations upon which temperature limits of rating are based, and does not embody rules or limits for testing any specific type of apparatus. It establishes general principles with respect to temperature rise for the guidance of those responsible for the preparation of specific standards, and serves as an introductory chapter to the standards of the AIEE. Its especial purposes are to promote consistency between the various American and international standards for electrical apparatus, and to facilitate the understanding of differences in rating limits where these exist.

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or reject them entirely.

ALL letters submitted for consideration should be the original typewritten copy, double spaced. Any illustrations submitted should be in duplicate, one copy to be an inked drawing but without lettering, and the other to be lettered. Captions should be furnished for all illustrations.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

A Substitute for "Susceptance"

To the Editor:

In Group 05, Section 20, of the Proposed American Standard Definitions of Electrical Terms, sponsored by the Institute, are definitions for six ratios among the components of voltage and current between two points in an electric circuit: impedance and admittance, resistance and conductance, reactance and susceptance. In each of the first two pairs, the two terms have a similar significance and connotation, including that of their mutually reciprocal nature. In the last pair, however, the two terms are quite different in derivation and connotation.

It is interesting to note that the AIEE TRANSACTIONS (volumes 10 and 11, 1893 and 1894) of the days when complex quantities were first being applied to the computation of a-c circuits record prolonged discussions over the choice between "reactance" and "inductance" to designate the ratio of quadrature voltage drop to current. On the other hand, "susceptance" seems to have been adopted with hardly the suggestion of an alternative name. To open up the question at the present time may seem more academic than practical, but if a more appropriate term can be found, it would appear advisable at least to consider it. Terminology is not necessarily fixed or static; witness the comparatively recent displacement of the term "capacity" by "capacitance," and the still more recent change in application of the term "oersted."

The present definitions for reactance and susceptance depend upon the relative values of quadrature components of voltage and current, respectively, regardless of the means by which the phase displacements giving rise to these quadrature components may be brought about. Actually, the application of the two terms is confined largely, if not exclusively, to those displacements which result from the magnetic and electric fields associated only with the partial circuit question.

"Permeability" designates a certain magnetic characteristic of any medium. "Inductance" designates a magnetic characteristic of an electric circuit linking one or more magnetic media; the value of the coefficient of inductance depends upon the permeability of the media and the dimensions of the circuit. "Reactance" designates the ratio of that portion of the voltage reaction of a circuit which is due to its magnetic characteristics, to the alternating current causing this reaction; the value of this ratio depends upon the inductance of the circuit and the frequency of the current.

"Susceptibility" also designates a certain magnetic characteristic of any medium, and it is related to permeability in a linear manner. By an interchange of suffixes, this term is converted into "susceptance," which has been applied to the ratio of the quadrature component of current between two points in a circuit to the alternating voltage across them.

The logic and propriety of such a procedure is open to question on two grounds. First, it is entirely out of line with the steps which lead up to the term "reactance," as just outlined. It is true that "permeability," by a similar interchange of suffixes is sometimes converted into "permeance," but that term is confined to the magnetic circuit, where its significance is analogous to that of conductance in the electric circuit.

Second, the relation of capacitance to a quadrature current component is as simple and direct as that of inductance to a quadrature voltage component. Conversely, the relation of inductance to a quadrature current component is as involved as the relation of capacitance to a quadrature voltage component. Since the simple relation has been adopted for the quadrature voltage component, the relation of quadrature current component to applied voltage should be described in terms equally elementary. It therefore seems inappropriate to base a designation for this ratio upon the name of a magnetic characteristic of a medium.

While the ratio denoted by "reactance" is properly considered as a reaction, an electric current is more commonly regarded as an action that results directly from, or occurs with, the application of a potential difference or voltage. A term which conveys the idea can be obtained by substituting for the prefix "re-" one which means "with," as "con-" or "co-"; the alternative forms *conaclance* or *coaclance* result, either of which is a more truly descriptive name than "susceptance," is shorter by one or two letters, and has an interesting mnemonic feature. Impedance is now composed of resistance and reactance, and if the new term were adopted, admittance would be composed of conductance and *co(n)aclance*.

As a teacher of electrical subjects, the writer has for many years sought the most fundamental and widely used relationships, in order that the new and discrete concepts which the students are required to master may be as few in number and broad in

application as possible. It is this aim which motivates this questioning of the old term "susceptance," because it is believed that a more significant word will assist in clearing up what might be called one of the minor "untidinesses of the electromagnetic theory" referred to by Professor Synge at the 1937 convention of the Society for the Promotion of Engineering Education, in Cambridge, Mass.

The usual procedure is to introduce the students to resistance, inductance, and capacitance as independent concepts, the two latter manifesting themselves only when the current or voltage is changed in magnitude. When periodic changes are considered, it is demonstrated (by maintaining at a constant magnitude the current through an inductive coil, as measured by, say, a dynamometer instrument, and noting that a much higher applied voltage is required for alternating current than for direct), that alternating current generates a voltage reaction not produced by direct current. It then develops that much the greater part of this additional voltage reaction has a quadrature relation to the voltage reaction of the coil resistance, and, like the latter reaction, is proportional to the alternating current; the new proportionality factor is called reactance and is equal to the product of the coil inductance and an angular velocity corresponding to the frequency. The relationship of the total alternating voltage to the current is symbolized by the equation

$$\frac{\dot{E}}{\dot{I}} = Z = R + jX = R + j\omega L$$

This state of affairs is somewhat puzzling and its mastery is usually somewhat complicated and delayed by the introduction of another circuit constant, capacitance. By treatment that is usually analytical, rather than experimental, it is pointed out that the voltage reaction due to this new circuit element is also in quadrature with the voltage reaction due to resistance, and at the same time, opposite in phase to the voltage reaction due to inductance, and proportional, not to the capacitance, but to the reciprocal of the product of the capacitance and the angular velocity. Symbolically, this new reactance

$$-X_c = -1/(\omega C)$$

This method of handling capacitance produces in the mind of the thoughtful student many troublesome questions, some of which may require a long experience for a satisfactory answer. In the first place, there is the matter of the reciprocal itself; that, however, is a definite thing, susceptible of analytical proof, and can be utilized by rote, without complete comprehension.

The second question relates to resistance. The student comprehends the resistance of the coil and of the rest of the circuit and realizes that it must properly be considered as part of the coil impedance. But he also remembers that, by virtue of its construction, a capacitor is virtually an open circuit and therefore of infinite resistance, although little or no account of this resistance is taken in considering the voltage reaction of a capacitor. His confusion is not diminished when he comes to take the reciprocal of his impedance and finds that he cannot take the reciprocal of his reactance directly, and write $1/(\omega L)$, but must go through a process of inversion and rationalization which gives even the relatively small resistance of the coil a counterpart in the resulting admittance.

Sooner or later the student will have to do with a capacitance in which the losses are not negligible, and then he will learn that $1/(\omega C)$ is sometimes no more correct for the value of an elastive reactance than $1/(\omega L)$ is for a susceptive *co(n)actance*. Then he may realize that the reason it has been possible to state

$$X_c = -1/(\omega C)$$

as a fundamental relationship is the fortuitous circumstance that the frequencies, flux densities, and construction materials in common use hitherto have been such that the energy losses in a capacitor have generally been negligible, while the losses in a coil are usually considerable.

With the commercial development of capacitors of relatively large capacitance, and the use of higher frequencies, it would seem the time has come to develop a general treatment of capacitance co-ordinate with that given to inductance; that is, let the fundamental case include the losses, with the special case resulting from the circumstance that the losses may be negligible treated as a simplification of the general case.

Consider how closely such a fundamental treatment may be made to follow, but with a characteristic distinction, the procedure by which the components of impedance are derived. It may be demonstrated (by maintaining at a constant magnitude the *voltage across* a capacitance, as measured by, say, a dynamometer instrument, and noting that a very much greater *current* results from an alternating *voltage* than from a constant unidirectional voltage) that an alternating *voltage* generates a current component not produced by a constant rectified *voltage*. It may then be developed that much the greater part of this additional *current* has a quadrature relation to the conductance *current* of the capacitor, and, like the latter component, is proportional to the alternating voltage; the new proportionality factor may be called *co(n)actance* and is equal to the product of the capacitor capacitance and the angular velocity corresponding to the frequency. The relationship of the total alternating *current* to the *voltage* is symbolized by the equation

$$\frac{\dot{I}}{\dot{E}} = Y = G + jB = G + j\omega C$$

Thus we have the co-ordinate and fundamental relationships; in both of which, be it noted, the quadrature component is positive:

1. (Inductive) Impedance is composed of resistance and (inductive) reactance.

2. (Capacitive) Admittance is composed of conductance and (capacitive) *co(n)actance*.

These but paraphrase Doctor Steinmetz's statement of some years ago that the four fundamental constants of an electric circuit are resistance, reactance, conductance, and susceptance.

An impedance and an admittance cannot be combined with each other except by the process of inversion and rationalization. This step then becomes associated equally with the handling of either impedance or admittance, and is to be regarded as a normal and expected procedure to be mastered, instead of a tedious expedient to be avoided.

Even with the possible adoption of a term like *co(n)actance*, "susceptance" could still be given a useful place in the terminology by using it with reference to inductance, much as elastance is used with reference to capacitance.

Then, in addition to the fundamental impedance and admittance concepts, there are two secondary concepts derived by inversion:

Elastive impedance, composed of elastive resistance and elastive reactance,

$$Z_e = \frac{1}{Y} = \frac{G}{Y^2} - j\frac{B}{Y^2} = R_e - jX_e$$

and susceptive admittance, composed of susceptive conductance and susceptive *co(n)actance*,

$$Y_s = \frac{1}{Z} = \frac{R}{Z^2} - j\frac{X}{Z^2} = G_s - jB_s$$

Of course, any of the four constants which do not appear in one of the fundamental equations will have no counterpart in the respective derived equation. Hence for special conditions it would still be true that

$$X_c = -1/(\omega C)$$

In view of these considerations it is suggested that the question of a more significant name for the ratio now designated by "susceptance" be taken under consideration by the proper committee of the Institute.

Yours very truly,

A. A. Nims (A'11, M'28)

(Professor of electrical engineering, Newark College of Engineering, Newark, N. J.)

Graduate Training for Engineers

To the Editor:

It is very gratifying to one who has given much thought to the subject of education for engineers to note that at least one branch is receiving serious consideration. The general trend of electrical-engineering development makes it imperative to give the matter most serious consideration. The article entitled "Graduate Training for Engineers" lays down the general problem most capably but I disagree with the proposition put forward that the solution to the problem of training men having "the ability to do new and difficult feats in industry" is to be found in postgraduate training.

The principle of producing an article capable of general application and then modifying it to do a specific function is bad engineering practice, so why should one apply such an evil principle to the most vital function of engineering—the training of its personnel. The opinion of administrative heads of firms that postgraduate training is a waste of time is well founded on their engineering instincts. If there is any correcting to be done, they prefer to do it themselves.

A point which I consider has not been properly considered in the past is that engineers may be divided into three broad cate-

gories, namely: development engineers, applicational engineers, and operational engineers.

A development engineer is one whose function is to advance his particular branch of engineering by the development of new materials and equipment—in fact one who stands on the borderline between pure science and engineering.

The applicational engineer is an engineer proper with a bent in a particular direction—that of applying the products of his branch to the use of mankind. The work carried on by such an engineer includes what is commonly known as design work in engineering manufacture, or the activities of sales engineer (as distinct from a salesman) applying his equipment to the various functions required.

An operational engineer is one who controls the generation and distribution of electricity or the manufacture of electrical products.

The educational and training requirements for the three branches are, I submit, entirely different and I consider a great deal of time, valuable energy, and money is wasted in trying to provide a curriculum that will turn out engineers suitable for any of the three.

The attainments of most men are governed by their environment. Thus a development engineer must be so educated that he numbers amongst his acquaintances scientists; an operational or an applicational engineer must be so educated as to number amongst his acquaintances development engineers. For this purpose I support the creation of technological colleges, but not with quite the same aim as Mr. Morrow.

The major tool in the equipment of any engineer embarking on advanced development is mathematics, followed at a distance by a comprehensive knowledge of chemistry and physics. The aspirant to the position of development engineer must, therefore, show an exceptional aptitude for mathematics. If in completing his secondary-school studies to the standard of the matriculation examination of the University of London the boy shows ability in mathematics and wishes to become an engineer, he should be given an opportunity of going to a university where his graduate study should be mathematics to a very high standard—not less than the mathematical tripos of Cambridge University, with physics and chemistry as secondary subjects.

He could then take his engineering as a postgraduate course at a technical college, this training being followed by two years of actual work as an apprentice in an engineering works. Thus, for the most advanced branch of engineering, I advocate the postgraduate training of a mathematician in engineering, and not vice versa. My reasons for this are: first, experimental results, that is, I have met young men who have been correctly guided into taking this course and the result is brilliant. The explanation is of course quite simple, in that the principles of engineering are relatively simple, but the mathematical working-out is not always easy. While the normal student is struggling to understand the mathematical steps, the mathematical graduate sees the result in advance and can concentrate on the principles and the implications of the result. The second is my experience in coaching both types of students, where the contrast cited simply "hits one in the face."

I agree with Mr. Morrow that it is not necessary for manufacturers to offer any specific inducement to engineers with high training as, if they have the personality to apply their training, they will rise to the highest positions by their own natural "development potential."

The applicational engineer is of different type. His major requirement is quickness of thought and breadth of vision, since it is he who to a great extent sets the problems for the development engineer. I personally do not consider that a university education, as it is understood in England, is essential to the applicational engineer. The training should be given by a technical college where development engineers are taking their postgraduate course. The latter could assist the faculty and gain valuable training themselves by taking junior classes in mathematics, physics, and chemistry. The training should be carried out in conjunction with an engineering works. Thus on leaving a secondary school, that is, having knowledge to the London University matriculation standard, the student should be put for a year into an engineering works with the insistence that he attend evening classes to continue his studies. It should be possible for him during this year to attain the standard of the intermediate examination for external students of the London University. If possible, arrangements should be made with the works to allow the student one day per week to attend at the college all day, and he should be retained by the firm until he has passed his intermediate examination, say up to a maximum of two years. Having passed his intermediate examination and having seen from his engineering shop training the object of his future studies, the student should be given two years full-time technical training at the technical college, culminating in an examination to the standard of the honours degree in engineering of the London Uuiversity. This should then be followed by two years in an engineering works.

The result of such a training will be that the graduate will have a very thorough foundation in engineering and will have sufficient mathematical and scientific knowledge to understand the language talked by the development engineers, but he will have a much wider practical knowledge and will think in terms of machines. If he is an electrical engineer, he will be capable of interpreting the requirements of mechanical drives into electrical specifications and will be able to select the correct equipment for a given duty and indicate to the development engineer where there are gaps in the equipment available.

It is possible and highly desirable to give postgraduate training to this type of engineer but this must follow, not precede, the two years of apprenticeship. It is very difficult to know how this postgraduate training, preferably in economics, industrial administration, and his own specialty, can be given. The only solution is some form of evening lectures, but these are not very successful in so far as I have been able to observe, since after having worked hard for many years, the young man feels it is time he had some time to himself to take an interest in world affairs and what I euphemistically call the humanities.

The operational engineer is required to handle men and apart from the actual production of commodities, his contribution to the general weal is to prevent industrial strife. To do this he must understand the men he handles and to do this he must be one of them, be able to think as they think, and yet at the same time not lose his personality as an administrator and in effect an employer. In all probability this is the most difficult of all engineering functions and no man should undertake it who does not have a great "love" for his fellow men. The only way to acquire the mental flexibility of looking at one's actions from the point of view of the workman is to have been a workman oneself. No amount of theoretical training will give this faculty. It is therefore suggested that on leaving the secondary school with learning to the standard of the London matriculation, the boy at the age of 17 should go straight into an engineering works for a comprehensive apprenticeship course of four years, doing exactly the same work as a boy training to be a skilled workman but on a wider basis and with the requirement that he should study in his spare time by means of part-time day (one day per week) and evening classes. The student must attain a theoretical standard not less than that required of the applicational engineer. Not many, unfortunately, survive, but those that do and have a suitable character are superexcellent. Few are able to complete their theoretical training within the four years (the writer actually took six) but on completion of their four-year apprenticeship, the students will be admirably suited for the position of junior production engineer or time-study engineer and will be able to complete their technical training in their spare time. It is essential that the firm should give sympathetic consideration for time off to sit for examinations, in addition to normal holidays, in spite of the fact that the young man is virtually no longer a trainee but a normal member of the staff.

If the operational engineer wishes to take up generation, transmission, and distribution in electrical engineering or traction work, he will endeavour to obtain a junior position with a utility company or an electrified railroad, on the completion of his apprenticeship, but the general scheme of training is the same.

Postgraduate training can be also given to this type of engineer with greater benefit than to any other, but how this should be carried out is a problem for industry and the universities to solve together. And on their solution as to how to give this postgraduate training to applicational and operational engineers perhaps depends the future of engineering and consequently the whole of our civilization.

The training outlined here for any of the three types is undoubtedly arduous. Many will fall out along the way and provide the necessary technical intermediate staff but those that do survive will be able to carry on the great tradition of engineering and continue as the mainstay of our present civilization and culture.

Yours very truly,

N. V. Pestereff

(Purchasing assistant electrical engineer, The Canadian and General Finance Company, Ltd., London, England)

Personal Items

E. S. Lee (A'20, F'30) engineer in charge, general engineering laboratory, General Electric Company, Schenectady, N. Y., has been appointed chairman of the Institute's committee on constitution and bylaws for the year 1939–40. He has been a member of the committee since 1937. Mr. Lee, who was born at Chicago, Ill., November 19, 1891, received the degree of bachelor of sci nce in electrical engineering at the University of Illinois in 1913 and that of master of science in electrical engineering from Union College in 1915. From 1913 to 1916 he was an instructor in electrical engineering at Union College and a laboratory assistant at the General Electric Company in Schenectady, N. Y. He was with the Locomotive Stoker Company, Chicago, Ill., 1916–17, and during the next year was in charge of machine-gunnery at the United States Army school of military aeronautics at the University of Illinois, Urbana. Since 1918 he has been affiliated continuously with General Electric, becoming assistant engineer of the general engineering laboratory in 1928 and assuming his present position in 1931. He has been a director of the Institute, and chairman of the AIEE Schenectady Section. He has served on the executive, headquarters, Sections, and meetings and papers (now technical program) committees, and on the committees on membership (chairman 1933–36), finance (chairman 1936–37), and transfers (chairman 1937–39), and has been Institute representative on the division of engineering and industrial research of the National Research Council. At present he is a member of the committees on instruments and measurements, research, planning and coordination, the Edison Medal committee, and now and in the past has been active on special committees. Mr. Lee is also active in committee work in The American Society of Mechanical Engineers, American Society for Testing Materials, and American Standards Association.

J. W. Barker (M'26, F'30) dean of engineering, Columbia University, New York, N. Y., has been appointed chairman of the technical program committee and the committee on award of Institute prizes of the AIEE for 1939–40. He has been a member of the first since 1932 and of the second since 1937. Dean Barker was born June 17, 1891, at Lawrence, Mass., and received the degrees of bachelor of science in electrical engineering (1916) and master of science in electrical engineering (1925) from Massachusetts Institute of Technology. He served in the Coast Artillery Corps of the United States Army as artillery engineer and adjutant from 1916 to 1925, during part of the time being officer in charge of civil affairs of the American forces in Germany. Appointed associate professor of electrical engineering at Lehigh University, Bethlehem, Pa., in 1925, he became professor and head of the department in 1929. Since 1930 he has been professor and dean of the faculty of engineering at Columbia University. He has served on the Institute's committee on production and application of light and is at present a member of the publication, planning and co-ordination, Edison Medal, and education committees, having been chairman of the last-named 1937–39. He is Institute representative on the Iwadare Foundation and the United States national committee of the International Commission on Illumination. He is a member of several other technical societies and has been active in the division of engineering and research of the National Research Council.

F. Ellis Johnson (A'13, F'31) dean of the college of engineering, University of Wisconsin, Madison, has been appointed chairman of the Institute's committee on education for 1939–40. He has been a member of the committee during 1933–35 and since 1936. Born May 27, 1885, at LeRoy, Mich., he received the degrees of bachelor of arts (1906) and electrical engineer (1909) from the University of Wisconsin. Following a period of employment in substation construction in the western United States and Canada, he became an instructor in electrical engineering at The Rice Institute, Houston, Tex., in 1912. He entered the electrical-engineering department of the University of Kansas, Lawrence, as an instructor in 1915, and advanced through the grades of assistant professor, associate professor, and professor, to become head of the department in 1928. In 1930 he went to Iowa State College, Ames, as head of the department of electrical engineering, and in 1935 he became dean of the college of engineering, University of Missouri, Columbia, assuming his present position at Wisconsin in 1938. He has been a director of the Institute and member of the committees on membership and on Student Branches (chairman 1936–38). He is currently a member of the committee on electrical machinery, and an Institute representative on the Engineers' Council for Professional Development.

W. F. Davidson (A'14, F'26) director of research, Consolidated Edison Company of New York, Inc., New York, N. Y., has been appointed chairman of the AIEE committee on research for 1939–40. He has been a member of the committee since 1925. Born at Commonwealth, Wis., October 21, 1890, he received the degrees of bachelor of science (1913) and master of science (1920) from the electrical-engineering department of the University of Michigan. He was with the Westinghouse Electric and Manufacturing Company, Pittsburgh, Pa., 1914–16, and became an instructor at the University of Michigan, Ann Arbor, in 1916, returning in 1919 after two years' service in the United States Army. He became associate professor in 1920. In 1922 he went with the Brooklyn, N. Y., Edison Company to organize its research department, which was expanded under his direction to include research and testing activities in all the company's fields of interest. When the Brooklyn Edison Company became a part of Consolidated Edison of New York in 1936 he assumed his present position. He is a member of the committees on the award of Institute prizes and on basic sciences (formerly committee on electrophysics, of which he was chairman 1934–36).

J. C. Parker (A'04, F'12) vice-president, Consolidated Edison Company of New York, Inc., New York, N. Y., and junior past-president of the AIEE, has been appointed chairman of the Institute's committee on planning and co-ordination for the year 1939–40. Born at Detroit, Mich., April 15, 1879, he received the degrees of bachelor of science in mechanical engineering (1901), master of arts (1902) and electrical engineer (1904) from the University of Michigan,

J. C. PARKER

W. F. DAVIDSON

J. W. BARKER

F. ELLIS JOHNSON

E. S. LEE

A. L. POWELL

W. S. FINLAY, JR.

F. O. McMILLAN

H. S. OSBORNE

D. W. ATWATER

and the honorary degree of doctor of engineering from Stevens Institute of Technology in 1935. He was in the testing department of the General Electric Company, Schenectady, N. Y., 1902–3, and the following year was an instructor in mechanical and electrical engineering at Union College in Schenectady. In 1904 he became assistant to the engineer in charge of construction and design of the Ontario Power Company's plant at Niagara Falls, and the following year assistant to the chief engineer of the construction company building the lines of the Niagara, Lockport, and Ontario Power Company. As mechanical and electrical engineer he was transferred from Buffalo to Rochester, N. Y., by the construction company in 1907, and in 1908 was placed in charge of the engineering department of the Rochester Railway and Light Company. He was appointed head of the department of electrical engineering of the University of Michigan in 1915 and continued there until 1922, when he became associated with the Brooklyn, N. Y., Edison Company as electrical engineer. He became vice-president in charge of engineering in 1926 and president of the company in 1932, and in 1936, when the company became a part of Consolidated Edison of New York, became vice-president of the latter organization. He served the Institute as president, vice-president, member of the committees on Student Branches, education (chairman 1919–20), Sections, meetings and papers (now technical program committee), standards, power generation, power transmission and distribution, electrical machinery, the engineering profession, legislation affecting the engineering profession, and Lamme Medal committee, and as Institute representative on the American Standards Association. He is at present a member of the executive and Edison Medal committees, the committee on code of principles of professional conduct, and Institute representative on the John Fritz Medal board of award, and the division of engineering and industrial research of the National Research Council.

F. O. McMillan (A'14, F'32) head of the electrical-engineering department, Oregon State College, Corvallis, has been appointed chairman of the AIEE committee on transfers for 1939–40. He has been a member of the committee since 1936. Born at Albia, Iowa, May 12, 1890, he received the degrees of bachelor of science in electrical engineering (1912) from Oregon State College, and master of science in electrical engineering (1919) from Union College. From 1913 to 1920 he was employed by the General Electric Company, Schenectady, N. Y. Appointed assistant professor of electrical engineering at Oregon State College in 1920, he became associate professor in 1923, research professor in 1930, and head of the department in 1938. He has also been consulting engineer for the United States Bureau of Fisheries, the Port of Portland, Ore., the Northwest Electric Light and Power Association, and other organizations. He has been a vice-president of the AIEE and has served on the committees on Student Branches and basic sciences, and is at present a member of the committees on research and on education. He is a member of several technical societies.

D. W. Atwater (A'24) manager of commercial engineering, lamp division, Westinghouse Electric and Manufacturing Company, Bloomfield, N. J., has been appointed chairman of the AIEE committee on production and application of light for the year 1939–40. He has been a member of the committee since 1935. Born August 14, 1894, at Newark, N. J., he received the degree of mechanical engineer from Stevens Institute of Technology in 1916, and became a factory engineer for the Edison Lamp Works, General Electric Company, Harrison, N. J. He was with the United States Army during 1917–1919, in the latter year becoming a specification engineer for the Western Electric Company, New York, N. Y. In 1920 he went with the lamp division of the Westinghouse Company, becoming assistant manager of the commercial engineering department in 1933 and manager in 1934. He has long been active in the Illuminating Engineering Society, of which he has been president and general secretary, and has been chairman of the illuminating group of the AIEE New York Section.

H. S. Osborne (A'10, F'21) operating results engineer, American Telephone and Telegraph Company, New York, N. Y., has been appointed chairman of the AIEE finance committee for 1939–40. He has formerly served on the standards, education, communication, and publication committees and as Institute representative on the United States national committee of the International Electrotechnical Commission. At present he is a director of the Institute, member of the technical program and award of Institute prizes committees, of both of which he was chairman 1936–39, and of the executive, headquarters, Edison Medal, and planning and co-ordination committees, and the committees on Institute policy and on legislation affecting the engineering profession, and Institute representative on the council of the American Association for the Advancement of Science, the Alfred Noble prize committee of the American Society of Civil Engineers, and the standards council and electrical standards committee of the American Standards Committee. A biographical sketch of Mr. Osborne appeared in the May issue, page 227.

W. S. Finlay, Jr. (A'18, F'21) has been appointed a vice-president of the J. G. White Engineering Corporation, New York, N. Y. Since 1927 he had been president of The West Penn Electric Company, New York. Born at Hoboken, N. J., August 18, 1882 he received the degree of mechanical engineer from Cornell University in 1904. From 1904 to 1909 he was an assistant engineer in the motive power department of the Interborough Rapid Transit Company, New York. During the next year he was engaged in engineering construction for the J. G. White company and the New England Engineering Company, New Haven, Conn., and from 1910 to 1915 in managerial work for E. and W. S. Finlay, New York. He returned to the IRT in 1915 as construction engineer, and was superintendent of motive power 1917–20. He became vice-president of the American Water Works and Electric Company in 1920, continuing in that position until he assumed the presidency of its subsidary, The West Penn Power Company, in 1927. He is a member of The American Society of Mechanical engineers.

A. L. Powell (A'13, F'26) supervising engineer, incandescent lamp department, General Electric Company, New York, N. Y., has been appointed chairman of the AIEE board of examiners for 1939–40. He has been a member of the board since 1929. Born April 6, 1889, at Brooklyn, N. Y., he received the degree of electrical engineer from Columbia University in 1910, and the same year was employed by the Edison lamp works of General Electric at Harrison, N. J. From 1911 to 1924 he was first assistant to the illuminating engineer, engaged in design and research work. During 1924–25 he was special representative in Europe for International General Electric

Company, and in 1925 he became manager of the engineering department of the Edison lamp works. He was transferred to his present position in 1932. He was a member of the United States Committee of the International Commission on Illumination at its meeting in Geneva, Switzerland, in 1924, and at its meeting in Germany in 1935, and a member of the United States Commission to the Paris Exposition in 1925. He is a member of the AIEE committee on production and application of light (chairman 1935–37) and a past-president of the Illuminating Engineering Society.

H. L. Hazen (A'26) head of the department of electrical engineering, Massachusetts Institute of Technology, Cambridge, Mass., has been appointed chairman of the AIEE committee on basic sciences for 1939–40. He became a member of the committee in 1938. Born August 1, 1901, at Philo, Ill., he studied electrical engineering at Massachusetts Institute of Technology, receiving the degrees of bachelor of science (1924), master of science (1929), and doctor of science (1932). He joined the teaching staff of MIT in 1926, becoming associate professor in 1936, and professor and head of the department in 1938. During 1934–35 he served as exchange professor at Ohio State University, Columbus. In addition to his academic work, he has had experience in the laboratories of the General Electric Company and the American Telephone and Telegraph Company. He received the 1934 Levy Gold Medal of the Franklin Institute for technical papers on the theory and design of servo-mechanisms.

I. F. Kinnard (A'21, M'28) executive engineer, West Lynn works, General Electric Company, Lynn, Mass., has been appointed chairman of the AIEE committee on instruments and measurements for the year 1939–40. He has been a member of the committee since 1927. Born in Ontario, Can., September 29, 1891, he received the degree of bachelor of science in electrical engineering from Queen's University, and did advanced work both at Queen's and at the University of Glasgow. After service overseas as an officer in the Canadian Engineers, he became a research engineer for Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., in 1920. He went to the West Lynn works of General Electric as an electrical engineer in 1923, where he did research on electrical instruments. He was appointed assistant chief engineer in 1923, and later executive engineer.

C. R. Beardsley (A'08, F'30) manager, contract control and inspection department, Consolidated Edison Company of New York, Inc., New York, N. Y., has been appointed chairman of the Institute's committee on legislation affecting the engineering profession, for the year 1939–40. He has been a member of the committee since 1937. A director of the Institute, Mr. Beardsley is also a member of the Edison Medal and technical program committees, and was chairman of the special committee on model registration law. A biographical sketch of him appeared in the April issue, page 183.

E. E. George (A'20, F'36) has been appointed a member of the engineering staff of Phoenix Engineering Corporation, New York, N. Y., a subsidiary of Ebasco Services, Inc. He was formerly superintendent of system operation, Tennessee Electric Power Company, Chattanooga. A biographical sketch of Mr. George appeared in the March issue, page 135.

K. T. Compton (F'31) president, Massachusetts Institute of Technology, Cambridge, has been appointed to the newly formed War Resources Board, which is designed to plan the mobilization of the economic and industrial resources of the United States in the event of war.

T. S. Taylor (M'21) has become a member of the teaching staff of Newark College of Engineering, Newark, N. J. He was formerly manager of the engineering laboratory and experimental department, Diehl Manufacturing Company, Elizabethport, N. J.

Chester Russell, Jr. (A'29, M'34) formerly associate professor and head of the department of electrical engineering, University of New Mexico, Albuquerque, has become associate professor of electrical engineering at the University of Denver, Denver, Colo.

E. M. Manos (A'38) has been employed as electrical draftsman and estimator by the North State Electric Company, Chicago, Ill.

W. S. Gifford (A'16) president, American Telephone and Telegraph Company, New York, N. Y., has been appointed a member of the War Resources Board, recently organized to plan mobilization of the economic and industrial resources of the United States in the event of war.

Obituary

Glen Harry Smith (A'20, M'26) assistant superintendent, municipal electric power generating and distributing system, City of Seattle, Wash., died at Louisville, Ky., September 10, 1939. He was born March 31, 1885, at Loveland, Colo., and studied at the University of Washington, receiving the degrees of bachelor of arts (1909) and bachelor of science in electrical engineering (1910). He had been employed by the lighting department of the City of Seattle since 1909, having been an oiler, substation operator, wiring draftsman (1912), engineer, overhead distribution (1917), and engineer, outside construction, from 1918 until his death. Since 1917 he had been in charge of operation and construction of distribution and transmission for the Seattle municipal system. He was vice-chairman of the AIEE Seattle Section.

David Rhett Pringle (A'07) utilities superintendent, City of Thomasville, Ga., died August 4, 1939. He was born in Leon County, Florida, August 24, 1882, and graduated with the degree of bachelor of science in electrical engineering at the Georgia Institute of Technology in 1904. He spent three months in the student course of Western Electric Company, New York, and from October 1904 to January 1906 was employed by the Gray National Telantograph Company, New York. He became superintendent of the municipal electric light plant at Thomasville in January 1906, when the plant was first placed under municipal operation, and had charge of the development of the expanding system until his death.

Charles Arba Storms (A'26, M'36) electrical engineer, Michigan Limestone and Chemical Company, Rogers City, died August 21, 1939. Born September 23, 1899, at Fargo, N. Dak., he received the degree of bachelor of science in electrical engineering from California Institute of Technology in 1923. He was employed in the test department of the General Electric Company, Schenectady, N. Y. from 1923 to 1929, during the last two years of that time as foreman of the construction section. Since 1929 he had been electrical engineer for the Michigan Limestone and Chemical Company, having charge of design, construction, and operation of various electrical installations.

Adhemar Machado de Sousa (A'28), first assistant engineer, Sao Paulo Tramway, Light, and Power Company, Sao Paulo, Brazil, died recently, according to information received at AIEE headquarters. He was born December 10, 1903, at Santos, Sao Paulo, Brazil, and graduated with the degree of electrical engineer from the Polytechnic School of Sao Paulo in 1927. In 1928 he was employed as apprentice engineer in the department of electrical studies and investigations of the Sao Paulo Tramway, Light, and Power Company, and continued with the company until his death.

C. R. BEARDSLEY

H. L. HAZEN

I. F. KINNARD

Membership

Recommended for Transfer

The board of examiners, at its meeting on September 14, 1939, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Cadwallader, J. A., engineer of transmission and outside plant, The Bell Telephone Company of Pennsylvania, Pittsburgh.

Edmondson, F. C., general manager, City of Perth Electricity and Gas Department, Perth, Western Australia.

MacGregor, J. R., chief engineer, The Bell Telephone Company of Pennsylvania, Pittsburgh.

Mier, C. W., area engineer, Southwestern Bell Telephone Company, Dallas, Tex.

4 to Grade of Fellow

To Grade of Member

Adler, L. E., communication engineer, Magnolia Pipe Line Company, Dallas, Tex.

Chiles, J. H., section engineer, Westinghouse Electric and Manufacturing Company, Sharon, Pa.

Dalziel, C. F., assistant professor, University of California, Berkeley.

Dunham, H. E., assistant manager, patent department, General Electric Company, Schenectady, N. Y.

Fiedler, G. J., instructor in electrical-engineering department, Union College, Schenectady, N. Y.

Hobson, L. S., managing engineer, General Electric Company, Philadelphia, Pa.

Jadeja, K. K. R., chief electrical engineer, Nawanagar State Power House, Jamnagar, India.

Kelm, A. C., superintendent of electric service, Utah Power and Light Company, Salt Lake City.

Nartker, L. J., electrical engineer, Sunlight Electric Division of General Motors Corporation, Warren, Ohio.

Plomasen, C. G., electrical engineer, Eastman Kodak Company, Rochester, N. Y.

Sandberg, S. I., electrical-engineering designer, City of San Francisco, Calif.

Schols, H. J., supervising electrical engineer, Commonwealth and Southern Corporation of New York, Birmingham, Ala.

Weaver, E. F., division superintendent, Pennsylvania Power and Light Company, Allentown.

13 to Grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Names of applicants in the United States and Canada are arranged by geographical Districts. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before October 31, 1939, or December 31, 1939, if the applicant resides outside of the United States or Canada:

United States and Canada

1. NORTH EASTERN

Gifford, F. A., New England Telephone and Telegraph Company, Boston, Mass.

Hammond, J. W., Jackson and Moreland, Boston Mass.

Osborn, A. L., Orange and Rockland Electric Company, Monroe, N. Y.

Sheals, V. A. (Member), General Electric Company, Schenectady, N. Y.

2. MIDDLE EASTERN

Hudson, H. A., Southern Railway System, Washington, D. C.

McOrily, J. (Member), Edwin L. Wiegand Company, Pittsburgh, Pa.

Tomb, R. N., 113 Hammer Avenue, Johnstown, Pa.

3. NEW YORK CITY

Adamson, A. A., Bell Telephone Laboratories, Inc. New York, N. Y.

Cawthorne, T. S., Weston Electrical Instrument Corporation, Newark, N. J.

Hughes, K. E. (Member), The Hickok Electrical Instrument Company, Cleveland, Ohio, New York, N. Y.

Hyde, G. G. (Member), Consolidated Edison Company, New York, N. Y.

Oberkirk, W. C., Wilbur B. Driver Company, Newark, N. J.

4. SOUTHERN

Storey, S. B., Trumbull Electric Manufacturing Company, Ludlow, Ky.

Wilder, A. N., Tampa Electric Company, Plant City, Fla.

5. GREAT LAKES

Beckjord, P. A., Jr., Westinghouse Electric and Manufacturing Company, Chicago, Ill.

Hudson, M. B., Illinois Iowa Power Company, Edwardsville, Ill.

Johnson, F. M., Swift and Company, Chicago, Ill.

Sutherland, R. O., United Light and Power Service Company, Chicago, Ill.

6. NORTH CENTRAL

Mitchel, G. W., Black Forest Fox Ranch, Monument, Colo.

7. SOUTH WEST

Conner, J. M., Nevada Consolidated Copper Corporation, Hurley, N. Mex.

Hahn, H. E. (Member), Federal Engineering and Construction Company, Kansas City, Mo.

LeDoux, A. E., El Paso Electric Company, El Paso, Tex.

Riegel, P. R., Sun Oil Company, Beaumont, Tex.

Starcke, C. A., United Light and Power Service Company, Kansas City, Mo.

8. PACIFIC

Koch, C. R., Westinghouse Electric and Manufacturing Company, San Francisco, Calif.

Stahl, W. F., Jr., Stahl Ranch Company, Fallbrook, Calif.

9. NORTH WEST

Bachman, E. (Member), General Electric Company, Salt Lake City, Utah.

Total, United States, 27

Elsewhere

Chandrasekharan, V. A., care V. N. Raja and Company, Vellore, South India.

Kuramoto, H. H., Hawaiian Sugar Company, Makaweli, Kauai, T. H.

Page, G. B. (Member), Indian Cable Company, Ltd., Calcutta, India.

Rampal, J. N., Punjab Electric Power Company, Ltd., Montgomery, Punjab, India.

Richardson, R. C. H., Metropolitan Vickers Electric Company, Ltd., Glasgow, C 3, Scotland.

Seshachar, K. V., Tata Iron and Steel Company, Ltd., Jamshedpur, India.

Total, elsewhere, 6

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the addresses as they last appear on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Crawford, Wade P., Box 364, Coeur D'Alene, Idaho.

Doherty, Joseph F., 901 Hill St., Wilkinsburg, Pa.

Ebert, Kenneth W., 770 N. Cass St., Milwaukee, Wis.

Hall, John R., c/o Patrick Tyrrell Drilling Co., Cotton Exchange Bldg., Houston, Texas.

James, George Hazard, Jr., 7 Meikle Ave., Newport, R. I.

Keiser, M., 1841 Broadway, New York, N. Y.

Lovett, Morris, Diehl Manufacturing Company, Elizabethport, N. J.

McCarthy, C. C., c/o Westinghouse Electric and Manufacturing Co., 814 Ellicott Square, Buffalo, N. Y.

Modisette, M. H., 4514—16th St., N. E., Seattle, Wash.

O'Fiel, J. C. Dudley, Jr., 1214 Chartres St., Houston, Texas.

Pyne, Arnold N., 627 Third St., Niagara Falls, N. Y.

Sanchez, Hector M., 12 De Diegos Ave., Santurce, Puerto Rico.

Strauss, Walter A., 30 West 69th St., New York, N. Y.

Taylor, Richard V., Hotel Wood, Jefferson & Clinton St., Syracuse, N. Y.

Williams, Robert E., Jr., 1038 Wendell Ave., Schenectady, N. Y.

15 Addresses Wanted

Engineering Literature

New Books in the Societies Library

Electrical engineers may be interested in the following new books, which are among those recently received at the Engineering Societies Library, New York, N. Y. Unless otherwise specified, books listed have been presented by the publishers. The Institute assumes no responsibility for statements made in the following summaries, information for which is taken from the preface of the book in question.

CO-OPERATION IN RESEARCH. By the Staff Members and Research Associates of the Carnegie Institution of Washington, Washington, D. C. 1938. 782 pages, illustrated, 10 by 7 inches, paper, $4.50; cloth, $5.00. This volume of papers written by members and research associates of the Carnegie Institution of Washington commemorates the retirement of President John C. Merriam. Among the papers of special interest to electrical engineers may be mentioned: An Adventure in Scientific Collaboration, by Arthur L. Day; Magnetism and the Atomic Nucleus, by M. A. Tuve, L. R. Hafstad, and N. P. Heydenburg; Universal Aspects of Atmospheric Electricity, by O. H. Gish; The General Magnetic Field of the Earth and Its Secular Variation, by J. A. Fleming; The Ephemeral Variations of the Earth's Magnetism, by L. V. Berkner and A. G. McNish; The Scientific Basis of the History of Science, by George Sarton.

REPORTS ON PROGRESS IN PHYSICS. Volume 5. Edited by A. Ferguson. London, S.W. 7, The Physical Society; Cambridge, England, University Press, 1938. 446 pages, illustrated, 10 by 7 inches, cloth, 20s. Continuing the series of reports issued by the Physical Society, the present volume deals with advances in physical science up to the end of 1937. It includes reviews of the work in general physics, sound, heat, astronomy, meteorology, optics, spectroscopy, electric-wave filters, and atomic physics; and more comprehensive articles on the adoption theorem of J. W. Gibbs, liquid-state theories, plastics in industrial physics, instrumental aids for defective bearing, soft X-ray spectroscopy, the use of X rays and Y rays in medicine, absolute electrical measurements, the Geiger counter, quantum mechanics, and physics teaching in schools.

REGULATIONS AND ORDERS RELATING TO SAFETY AND HEALTH. Mines Department, Great Britain Coal Mines Act, 1911. 1939 edition. 199 pages, tables, 10 by 6 inches, paper, 1s. 6d. (Obtainable from British Library of Information, 50 Rockefeller Plaza, New York, $0.45.) Intended primarily as a book of reference for mine officials, students of mining, etc., and contains, with a few exceptions, all the orders and regulations which are of general application in relation to matters of safety and health in the working of mines. Topics covered include first-aid and rescue methods, lighting, mechanical equipment, fire-fighting, signaling apparatus, explosives, and certificates of qualification for various jobs.

THE THEORY OF FUNCTIONS. By E. C. Titchmarsh. Second edition. New York, Oxford University Press, 1939. 454 pages, tables, 9 by 6 inches, cloth, $8.50. These introductory chapters to various branches of the theory of functions are intended to bridge the gap between the elementary textbooks and the systematic treatises. Chapter topics include infinite series, analytic functions, residues, analytic continuation, the maximum-modulus theorem, conformal representation, power series, infinite functions, differentiation, Lebesgue integration, and Dirichlet and Fourier Series. Bibliography.

USES AND APPLICATIONS OF CHEMICALS AND RELATED MATERIALS. Edited by T. C. Gregory. New York, Reinhold Publishing Corporation, 1939. 666 pages, 9 by 6 inches, cloth, $10.00. Over 5000 chemicals, drugs, metals, oils, and so forth, are listed alphabetically under their common names, each accompanied by a broadly classified list of present uses and potential applications. English synonyms, corresponding foreign names, and some patent references are also given. At the back of the book the synonyms and cross references are listed alphabetically.

MITTEILUNGEN AUS DEN FORSCHUNGSANSTALTEN, Bd. 7, Heft 3, April 1939, pages 41–66. Berlin, VDI-Verlag, 1939. Illustrated, 12 by 8 inches, paper, 2.90 rm. The three articles contained in this research communication deal respectively with the weldability of structural steel, with cog-wheel drives for electrically driven rolling-mills, and with the determination of wind loads on wide-span roofs by the use of a model.

Transactions

Papers and Discussions Comprising Pages 499–562 of the 1939 Volume

The Rating of Electrical Machinery and Apparatus

R. E. HELLMUND
FELLOW AIEE

THIS PAPER outlines briefly some of the technical, economic, and psychological aspects of the methods of rating electrical machinery and apparatus. Some proposed modifications of existing standards also are discussed, with the idea of bringing the standards into better agreement with present-day conditions, knowledge, and practices.

I. Objectives of an Ideal Rating Structure

Before discussing the present structure of rating standards and any changes therein, it may be well to set forth briefly the objectives of an ideal method of rating.

1. The ratings assigned to individual machines or devices under any adopted structure of standards should convey correct and useful information to their users. Therefore, they should indicate the load which can be carried with safety either continuously or for specified periods, and they furthermore should give reasonable assurance of satisfactory and economical operation from every point of view under typical or normal conditions. This might well be considered the primary purpose in assigning ratings. The information conveyed by the method of rating should, of course, make possible a fair comparison of competitive commercial products.

2. The system of standards should tend to bring about the most economical all-round application of electrical machinery and devices.

3. The entire structure of standard ratings should be as simple as possible in order to avoid confusion and consequent misapplication. Thus, the various American standards should be as uniform as possible and they should be as closely in accord with the international standards as they can be without interfering with requirements resulting from the particular conditions prevailing in this country.

In any attempt to meet these objectives, the psychological aspects of the rating structure should be given as much attention as the technical and economic. It should be realized that if the stamp of approval is placed upon certain values of temperature rise and corresponding ratings by experts in the industry, it should, and does, carry considerable weight with the laymen, the less informed technicians, and the engineers and creates the impression that such temperature rises and ratings are approximately correct for normal operation in actual service. The fact that a simple method of rating cannot give complete information for all conditions of service is no reason why the rating given to a machine should not be indicative of typical or normal conditions. If, for instance, ratings for class *B* railway motors are based on a temperature rise of 105 degrees centigrade, as has been done in one of the International Electrotechnical Commission standards, instead of on a rise of 120 to 130 degrees centigrade, which has been demonstrated to be both satisfactory and economical in the United States, the operating engineer naturally will not load the motors in service so that they operate at the higher temperature rises. In other words, the IEC method of rating undoubtedly will result in uneconomical applications. This illustration brings out a point of view entirely different from the one frequently expressed, namely, that the method of rating is useful merely in facilitating a fair comparison between competitive products.

As in many similar cases, it is impossible to meet these objectives in full because recognition cannot be given to some conditions without interfering with others. For example, a rating structure taking into account the most economical application may not at the same time have the desired simplicity; in which case, a reasonable compromise between the conflicting objectives should be adopted.

II. Present Standards and Practices

Almost since the beginning of the electrical industry, the basic principle of rating electrical apparatus has been to specify the temperature rise permissible either for continuous operation or for limited periods. The basic considerations, limiting values of temperature, and methods of testing are covered in AIEE Standard No. 1,[1] while standards applying to specific types of machinery are covered in various National Electrical Manufacturers Association and American Standards Association rules. Standards for international use have been established by the IEC. Since the maximum temperatures reached by the insulation cannot be determined by any of the present methods of determining temperature, namely, the thermometer, resistance, and embedded-detector methods, values somewhat below the maximum permissible temperatures have been selected as standards. The difference between the maximum temperatures and those obtained with the available methods of test varies with different designs; however, values covering conditions found in conventional designs have been selected as standards for these differences.

Although AIEE Standard No. 1 gives all three methods of measurement, the ASA and NEMA standards recognize only one of the three methods for some types of machines and their individual parts, the thermometer method being given in the majority of cases.[2] In other instances, as, for example, the tentative standards for traction apparatus, both the thermometer and the resistance method are recognized, but "the resistance method is considered as the rule."[3] Both the ASA and IEC transformer standards[4] specify the resistance method for windings. The international standards for machinery[4] specify embedded detectors for large

Paper number 39-6, recommended by the AIEE committee on electrical machinery, and presented at the AIEE winter convention, New York, N. Y., January 23–27, 1939. Manuscript submitted October 31, 1938; made available for preprinting November 29, 1938.

R. E. Hellmund is chief engineer of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

1. For all numbered references, see list at end of paper.

Figure 1. Comparison of a modern traction motor and a general-purpose industrial motor

Left—Traction motor, 125 horsepower based on temperature rise by resistance, 120 degrees centigrade in armature, 130 degrees centigrade in field; continuous speed, 1,450 rpm; weight per horsepower, 8 pounds

Right—Industrial motor, 125 horsepower based on temperature rise by thermometer, 40 degrees centigrade; continuous speed, 1,150 rpm; weight per horsepower, 25 pounds

machines, but in most other instances they recognize either the thermometer or the resistance method for windings, with implied preference for the resistance method. The thermometer method is of course specified for such parts as cores, commutators, etc., where the resistance method is not applicable. The same general practice is followed in the international standards for traction machinery,[6] but recent trends indicate that for this application the resistance method will practically eliminate the thermometer for any windings. (The subject of temperature measurement is discussed further in two contemporary papers.[7,8]) A greater degree of uniformity between these standards obviously is desirable, because with present-day knowledge there seem to be no sound reasons for some of the differences existing.

The standard temperature rises for continuous ratings usually have been selected with the intent of permitting continuous operation without injury to the insulating materials under an assumed ambient temperature of 40 degrees centigrade. An exception to this is the new ASA transformer recommendations which specify operation at an average ambient temperature of 30 degrees centigrade and a maximum of 40 degrees centigrade. The tentative standards for traction motors assumed, by inference, an average ambient of 25 degrees centigrade and a maximum of 40 degrees centigrade.

In addition to the continuous ratings discussed so far, overload ratings with temperature rises higher than those specified for continuous load are provided by some of our national standard rules for some types of electrical machines and apparatus. This is considered justified by the fact that deterioration of insulation is a question of both temperature and time and that satisfactory life can be obtained if higher temperatures are maintained only for short periods and at not too frequent intervals. Other commercial standards specify short-time ratings, the most typical among which is the one-hour rating for traction motors, which like any other short-time rating indicates to a certain extent the heat-absorption ability of the machine. (Short-time ratings are discussed in a contemporary paper by L. E. Hildebrand.[9])

In some instances the basic temperature rises specified in AIEE Standard No. 1 have been departed from, usually, however, for sound technical or economic reasons. For example: The temperature rise, by thermometer, for general-purpose motors has been specified as 40 degrees instead of 50 degrees centigrade, the limit given in Standard No. 1. This was done for the reason that general-purpose motors are often applied where the load is not exactly known and also by non-technical users, and a somewhat greater margin of safety was therefore considered advisable when the 40-degree standard was adopted. An extreme in the other direction is the temperature rise of 120 degrees, by resistance, specified for the armature and 130 degrees for the field in the tentative ASA standards for traction motors in comparison with the 75-degree rise specified in AIEE Standard No. 1. For traction work, higher temperatures and possibly a shorter life of the insulation may be justified by the economic gains possible through a reduction in the weight of and space occupied by the motors. Those familiar with railway problems know how important a reduction in size and weight is, not only in the motor itself but also in the resultant reduction in the truck and other parts. The use of small motors with higher temperatures in locomotives often makes it possible to reduce the number of driving axles and thus materially reduce the length and weight of the entire locomotive. In class *A* railway motors, armature coils have been found to have a shorter life than in industrial applications, but the expense for rewinding more frequently is compensated for by other economies gained. There is considerable evidence that class *B* insulation used in railway motors lasts almost indefinitely in spite of the increased temperature rises over those given in other standards. It is thus evident that in railway work a departure from the usual limits of temperature rise is fully justified by both economic considerations and actual practice.

Figure 1 shows the contrast in size which has resulted from the two most extreme departures from the temperature rises specified in Standard No. 1. At the left is a modern traction motor with class *B* insulation and designed for temperature rises (by resistance) of 120 and 130 degrees for the armature and field, respectively. At the right is a general-purpose motor of the same horsepower rating designed for 40 degrees temperature rise (by thermometer). The difference in the size of the two motors is marked; the weight of the traction motor is only about one-third that of the industrial motor. The speeds of the motors are different, but in both cases are in accord with those commonly used in the most modern practice for the particular applications. The fact that the large machine is not appreciably higher in cost than the small traction motor is surprising, but this is merely further evidence that the practices established for the two extreme cases are justified for the particular conditions to be met. While the adoption of the railway practice for general-purpose motors would result in reduced dimensions and weight, this would be of little value in most applications. On the other hand, it would mean disadvantages such as less accessibility of parts, reduced overload capacity on account of reduction

in mass, etc. The condition illustrated by the particular case cited—namely, that higher temperature rises are instrumental in reducing weight and size but have only a minor effect on cost—is found to hold true in many cases, particularly with the smaller sizes. The reason for this is that under crowded conditions of assembly, the expense for labor is likely to increase, and also because a change from class *A* to *B* insulation means an additional increase in cost of material with the present market prices of the class *B* materials involved.

The temperature rise of 55 degrees specified in the ASA standards for enclosed ventilated motors is another departure from the value specified in AIEE Standard No. 1. The difference of 5 degrees was adopted on the ground that temperatures within enclosed motors are usually more uniform than in open motors, resulting in a smaller difference between the hot-spot and measurable temperature. Furthermore, there is likely to be a decreased tendency toward deterioration of the insulation in fully protected windings.

It was early realized that the maintenance of safe temperatures was not the only condition to be met by commercial machines and apparatus. In addition to this, generators and transformers must have proper regulation; motors of all kinds must have sufficient starting and pull-out torque to meet prevailing service requirements; all commutating machines must give satisfactory commutation; machines and apparatus of all kinds must have efficiencies resulting in economical operation; a-c machinery must meet certain power-factor conditions; starting currents of motors must be limited to tolerable values; etc. In the realization of this, various standards set up by NEMA and ASA specify standard limiting values for the factors just mentioned. In arriving at these standard values, allowance has been made for reasonable variations in the power supply, particularly with reference to voltage. In practically all cases, however, the temperature rise remains the primary basis for rating and the other factors are usually looked on as supplementary standards.

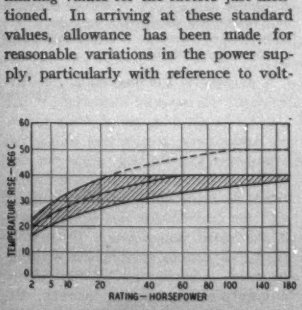


Figure 2. Band indicating actual temperature rises of general-purpose induction motors—four, six, and eight poles

In actual practice it frequently happens that in order to meet the requirements just mentioned, the apparatus has to be larger than dictated by temperature considerations, which in turn means that the actual temperature rises will be considerably below the specified standards, particularly for the lower ratings. In order to have economical manufacturing and stock conditions, the number of frame sizes for any line of machines or apparatus is limited, and as a result a frame size somewhat larger than necessary for the particular rating often has to be used, which again results in the actual temperature rise being lower than the specified standard. Figures 2, 3, and 4 show actual conditions for several types of apparatus.

Mention should be made of an increasing tendency to equip apparatus with thermal protective devices. Recent improvements in these devices and especially the high degree of protection which is possible with transformers are bound to result in better and broader utilization of the protected apparatus. At present the advantages of these protective devices are utilized in the application of apparatus, but eventually their use may influence the methods of rating.

III. Discussion of Changes in Rating Structure

One of the most important advantages of standards lies in the fact that valuable application experience is accumulated on the standards selected and any change nullifying such experience is likely to result in marked economic losses. Therefore, changes should be avoided unless worth-while advantages can be secured through them. In considering possible improvements in existing standards, it seems advisable first to consider minor modifications which would simplify and unify the present national and international structures of standards without causing difficulties of the nature just mentioned. Secondly, the various general practices which have been established and which are not in accord with the standards or are not recognized therein should be studied. If a critical examination of these practices indicates that they are sound in principle, the standards should be revised to recognize them. Finally, it should be determined whether on account of new developments and

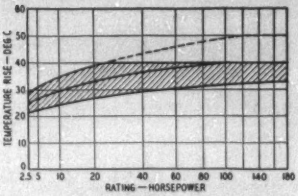


Figure 3. Band indicating actual temperature rises of general-purpose d-c motors having speed range of 850 to 1,750 rpm

experiences, certain changes in well-established standards and practices resulting therefrom are justified by the economies accomplished in the industry as a whole.

Following are a number of specific suggestions which, with the exception of a few minor changes proposed, relate essentially to supplementary provisions in the standards and are more of an evolutionary character; consequently they will not appreciably affect any standards or practices already in existence.

1. Early attention should be given to the following modifications in AIEE Standard No. 1:

A. The value specified for the temperature rise (by resistance) of class *B* insulation should be changed from 75 degrees centigrade to 80 degrees centigrade, the value specified in the IEC rules. The experience previously cited with class *B* insulation on railway motors indicates that this change is perfectly safe; furthermore, it means no hardship to manufacturers since existing designs would meet the new standard. A change of the 55-degree value, by resistance, for class *A* insulation to the IEC value of 60 degrees also seems desirable if investigation shows it to be safe.

Better agreement between AIEE Standard No. 1 and IEC standards could further be reached by lowering the class *B* thermometer value of 70 degrees in AIEE Standard No. 1 to 65 degrees, the value specified by IEC. However, it seems that this would be a step in the wrong direction in view of our railway experience, and, furthermore, the new value could not be met by existing designs.

B. A "Class *B*-1 Winding Practice," as distinguished from the ordinary class *B*, should be established.

The fact that long life and undoubted economies have been obtained in traction work with temperature rises for class *B* insulation far in excess of those specified in Standard No. 1 naturally suggests the idea that this be recognized in any revision of this standard. In formulating the new standard, a number of stipulations could be made in addition to those for ordinary insulation. Among them, the use of high-temperature soldering or brazing materials for joints and bands could be specified, as has been found expedient in railway practice. Precautionary statements could be added,

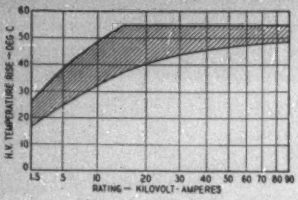


Figure 4. Band indicating actual temperature rises of distribution transformers of 2,400, 4,800, 6,900, 11,500, and 13,200 voltage classes

indicating, for instance, that the higher temperature rises should be adopted only where previous experience with machines of similar size and construction has demonstrated that satisfactory operation and life can be expected. (Various considerations which enter into this question other than direct deterioration of insulation by temperature are covered in a companion paper by C. Lynn.[10]) The availability of such high temperature standards would tend to establish a uniform practice if and when advantage is taken of the traction experience in other fields, such as aviation, navigation, and special industrial applications. Some consideration might be given to similar action in the use of class *A* insulation if this appears to be justified by a further study of operating experiences.

(As a matter of course, proper provisions for the application of glass insulation in connection with class *B* insulation and the suggested "Class *B*-1 Winding Practice" should be made in AIEE Standard No. 1 at the same time.)

C. Standard No. 1 should be revised to formulate and to recognize more definitely methods of rating and application other than those based on indefinite life with continuous full-load operation at an ambient temperature of 40 degrees centigrade.

Standards for reduced life expectancy should be established for use where this is considered economical. Recognition should be given to the usual condition of low average ambient temperatures, as has been done in the new transformer and traction apparatus rules. Short-time and intermittent-load conditions also should be covered by suitable provisions. These steps seem advisable because engineering and economic considerations cannot, and should not, be separated. A basic standard such as No. 1 should recognize their interrelation and establish guiding principles sufficiently flexible to cover varying economic conditions. Here again the available railway experience and practice may well serve as a guide. However, consideration should also be given to other economic conditions, as, for instance, motors built into various types of machinery, where on account of obsolescence or other factors, short life of the machinery is to be expected. In electrical machines for automobiles, for example, it would be a decided waste to apply insulation for an indefinite life expectance. Valuable data are given on intermittent-load applications in a contemporary paper by Alger and Johnson.[11]

Some of the points suggested may be covered by guiding principles for the application, but in other cases the rating structure may be involved and the most suitable procedure will have to be determined by further study.

2. In addition to the modifications just discussed, the following situations should be studied with the idea of improving various standards if and whenever revisions appear to be advisable.

A. As is generally appreciated, an ambient temperature of 40 degrees prevails only over relatively short periods in the majority of applications. This, together with the fact that deterioration of insulation is a function of both temperature and time, provides a margin of safety in all but a few exceptional applications. This and the further fact that machines and apparatus carry full loads continuously only in rare applications, makes it doubtful that the extra 10 degrees provided by the 40-degree rise of general-purpose motors is really warranted. However, a study of figures 2 and 3 indicates that up to 100 horsepower, the temperature rises of commercial machines would in general be below 40 degrees even with a 50-degree standard because the size of the machine is appreciably influenced by other considerations, such as starting and pull-out torques, power-factor values, commutation, etc. In other words, even granting that the additional margin provided by the 40-degree rating is not really necessary, no marked economies could be obtained by the 50-degree standard with the present established standards of performance relating to factors other than temperature. Therefore, at this time there seems to be no valid reason for disturbing the 40-degree standard for general-purpose motors up to about 100 horsepower; in fact, there is considerable merit, under conditions indicated in figures 2 and 3, in adhering to the 40-degree standard because it has the advantage of letting the user know that he can make use of the extra margin whenever conditions make this desirable. Thus the established standard of 40 degrees will lead to economies in some cases rather than interfere with maximum economy. The dotted lines in figures 2 and 3 show the temperature rises which might be obtained in actual practice with satisfactory all-round standards of performance if a 50-degree standard were established for 100 horsepower and above. From the figures it will be seen that slight economies might be obtained by limiting the 40-degree standard to the range below 100 horsepower.

Figure 4, applying to transformers, indicates that owing to the necessity for obtaining satisfactory regulation, the actual temperature rises in transformers are usually below the established standard of 55 degrees for ratings up to about 15 kva. Therefore, applying the same line of reasoning as given for general-purpose motors, a lower standard of temperature rise could be established for the lower ratings. On the other hand, since transformers are usually applied by specialists in electrical engineering who are in general familiar with the conditions indicated in figure 4, there is little need for making a change in well-established standards of rating. Furthermore, the increasing application of thermal devices indicating temperature rises in service may eventually assure the fullest and most efficient utilization of transformer capacities. This situation is covered fully in a paper previously presented by Messrs. Putman and Dann.[12]

B. Careful tests have demonstrated that if the oil in transformers is protected from contact with air so that it will not absorb any oxygen, there is practically no deterioration in insulating materials at the limits of temperature suggested by the AIEE and ASA standards. Similarly, there is considerable evidence that the insulation of hydrogen-cooled machines is subject to less deterioration than machines cooled by air. While for the present these advances may be taken advantage of by the methods of applying these machines and transformers with neutral atmosphere, serious consideration eventually should be given to the recognition of such improved operation in the AIEE and other standards. A careful study of the conditions necessary to assure this improved operation and their inclusion in the standards will be advisable.

C. Although there was merit in a single standard for the measurement of temperature by thermometer specified in many of the ASA and NEMA rules as long as the windings and other parts of machines were readily accessible, recent trends make it necessary to recognize in these standards the measurement of temperature by the resistance method, at least under some conditions. This change is brought about by the fact that an increased number of machines is being built in a way which makes windings and other hot spots inaccessible. Even where these parts may be reached by removing covers, too much time usually is consumed in doing so to permit accurate readings. In other apparatus, such as refrigerators and air-conditioning equipment, the motors are enclosed in such a way as to make thermometer readings entirely impossible or useless. In this connection, it should also be considered that in other countries the resistance method is generally preferred for motors, transformers, and generators for industrial and power purposes. More recently, at the insistence of the American representatives and others, the resistance method has been adopted by the IEC as the governing method for use with the windings of traction motors. This is another reason for giving more recognition to this method in many of our standards, although its immediate adoption in all cases and particularly in those where thermometer readings are possible, may not be found advisable.[8]

A proposition has been made recently, especially in a paper by Rutherford,[13] that a motor be rated on the starting torque per horsepower, accelerating torque per horsepower, and starting torque per ampere locked-rotor current. These factors should be taken into consideration along with the temperature rise of the motor at the rated horsepower. In another paper,[11] a system is proposed whereby the rating is based on a combination of temperature and starting current, the latter serving as an approximate measure of the torques. These methods are fully described in the papers and are mentioned

here principally for the sake of completeness.

Although the action suggested in this paper is by no means revolutionary, it would nevertheless tend to improve the existing structure of ratings appreciably by making it more uniform and putting it on a sound economic basis. It is evident that any standard must be kept up-to-date and that progress will be retarded materially and certain economies will not be accomplished if there is too much delay in recognizing economically and technically sound developments through suitable modifications and supplements to our standards. A careful study of the points mentioned here and also others given elsewhere relating to standards would, therefore seem appropriate, and it would seem that a revision of AIEE Standard No. 1 in particular is in order. Although mention has been made here of specific types of apparatus for the purpose of illustration, this should not be construed as suggesting that any specific type of apparatus be covered by Standard No. 1. This standard should in the future, as in the past, deal only with general principles and serve as a guide in establishing other standards for specific lines of machines and apparatus.

References

1. General Principles Upon Which Temperature Limits Are Based in the Rating of Electrical Machinery and Apparatus, AIEE Standard No. 1, April 1925.

2. American Standards for Rotating Electrical Machinery, ASA-C50, 1936.

3. American Tentative Standard for Railway Motors and Other Rotating Electrical Machinery on Rail Cars and Locomotives, ASA-C35, 1936 (AIEE No. 11, March 1937).

4. IEC Specification for Electrical Machinery, Part B—Transformers, IEC-28(Secretariat) 401

5. IEC Specification for Electrical Machinery, IEC Pub. 34 (Fourth edition, 1935).

6. IEC Rules for Electric Traction Motors, IEC Pub. 48 (First edition, 1933).

7. Measurement of Temperature in General-Purpose Squirrel-Cage Induction Motors, C. P. Potter. AIEE Transactions, volume 58, 1939, pages 468–72.

8. Determination of Temperature Rise of Induction Motors, E. R. Summers. AIEE Transactions, volume 58, 1939, pages 459–78.

9. Duty Cycles and Motor Rating, L. E. Hildebrand. AIEE Transactions, volume 58, 1939, pages 478–83.

10. Effects of Temperature on Mechanical Performance of Rotating Electrical Machinery, C. Lynn. AIEE Transactions, volume 58, 1939, pages 514–18.

11. Rating of General-Purpose Induction Motors, P. L. Alger and T. C. Johnson. AIEE Transactions, volume 58, 1939, pages 445–59.

12. Loading Transformers by Copper Temperature, H. V. Putman and W. M. Dann. AIEE Transactions, volume 58, 1939, pages 504–14.

13. The Rating and Application of Motors for Refrigeration and Air Conditioning, P. H. Rutherford. AIEE Transactions, volume 58, 1939, pages 519–27.

Discussion

E. F. Dissmeyer (The Commonwealth and Southern Corporation, Jackson, Mich.): No doubt there is justification for revision of certain present standards; however, extreme caution should be used in making any changes. It is unfortunate that there is not sufficient data available showing the relationship between operating temperature and the thermal life of various types of insulation. Consequently, the results of increasing the operating temperature of equipment cannot be predicted and our experiences may be costly unless caution is used in revising present standards.

Experience indicates that the temperature rise of a machine is indicative of its reliability and, for certain equipment applications, the permissible temperature rise should possibly be reduced. This is especially true for large machines where the loss of a machine usually results in serious consequences. Even under modern conditions, design errors and contingencies of manufacture and operation make it advisable to provide a margin of safety in the thermal design of a machine.

The reliability angle of this problem could be minimized by the development of suitable nondestructive tests which would make it possible to anticipate insulation failures. If it were possible to schedule replacement or rewinding of equipment, it would probably be possible to obtain an economic basis for increasing the permissible temperature rise of equipment.

R. E. Hellmund: The appeal made in the discussion of my paper for the use of extreme caution in changing standards is well justified and is in accord with statements in the paper itself. However, caution must not be carried to an extreme contrary to sound economic principles. It obviously would not be economical to establish rating standards which would give safe operation under any service conceivable; this would result in enormous waste in the majority of applications. The basic standard should be such that it results in safe and reliable operation in the large majority (possibly 75 to 85 per cent) of all applications, with a definite understanding that the remaining cases will be given special consideration in some way or other. The subcommittee of the AIEE standards committee, on basic principles for rating of electrical machines and apparatus, expects to undertake very extensive studies and to sponsor further papers and discussions on such phases as ambient temperature, life of insulation, allowances between hot-spot temperatures and temperatures measured by thermometer and resistance, etc.

I am at present of the opinion that the data so far available do not indicate the advisability of departing appreciably from present basic standards such as the temperature rise of 50 degrees by thermometer now specified in AIEE Standard No. 1 for class *A* insulation. In some cases this might be supplemented or replaced by the practically equivalent rise of 60 degrees by resistance. The practice of having more liberal commercial standards with temperature rises of 40 degrees by thermometer (possibly supplemented or replaced in some cases by a value of 50 degrees by the resistance method) probably should be continued to take care of cases where service conditions are more severe or where a greater margin of safety is desirable for some reason or other. Similarly, it may not be found advisable to change existing values materially for conventional class *B* applications, or those values which have proved satisfactory for transportation work and applications with similar economic and service conditions. However, final recommendations on all this should be withheld until some further investigational work which is now under way has been completed. During this period of study, it would be very helpful if operating engineers would assist to a greater extent in supplying pertinent and reliable data gathered from actual service experience.

Loading Transformers by Copper Temperature

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FELLOW AIEE

THE PURPOSE of this paper is to describe a new practical method of utilizing latent short-time overload capacity to the fullest extent, dependent upon actual copper temperature and automatically taking into account the factors that affect the life of a transformer.

It seldom happens in service that all the conditions established for the rating of a transformer exist concurrently and continuously and it is seldom the case that its maximum capacity is actually used for any great length of time. For these reasons it is realized that under many conditions transformers have an unused latent load capacity over and above their ratings, particularly for short time periods. That latent capacity depends upon the temperature to which the insulation can be safely exposed and how long it is exposed to it. Obviously ambient temperature plays its part for copper temperatures rise and fall with ambient temperature and the latent capacity is greater when the ambient temperature is low.

Users of transformers are naturally interested in making use of this latent overload capacity if a safe way can be devised for doing so. It is desirable for at least two reasons: first, the short-time overload capacity may be needed in emergencies due to the failure of some part of the system; second, short-time overload capacity can be used to carry peak loads and in that way reduce the average size of transformer required for a given load. The proper utilization of short-time overload capacity is therefore desirable in order to reduce costs and improve quality of service.

But how can the short-time overload capacity of transformers be utilized in practical system operation? The customer's load usually determines the loading of any particular unit and as a rule loads cannot be varied at will. In the case of distribution transformers, considerable effort on the part of the utility company is required in the direction of load surveys to determine the extent to which transformers are loaded. In the case of power transformers, graphic records of actual loads may be available, and in some cases hot-spot temperatures, but ordinary overload protection schemes will relay out a power transformer long before its maximum short-time overload capacity has been reached.

There are two parts to the problem of making use of latent overload capacity: first, the safe limits of temperature for different loads and time periods must be known; second, a practical method of operating up to but not beyond these temperature limits must be available.

Operating Temperature and Useful Life

Attempts have been made to establish a system of relationships between operating temperature and the useful life of a transformer. While they have been based upon data which are accepted as reliable under the conditions of test and upon reasoning which is not generally disputed, they are so far largely of academic interest as reports of progress rather than as tools of complete practical value in making use of the latent overload capacity of a transformer. Obviously, the positive and direct way of determining accurately the relation between life and temperature would be to provide a large number of transformers and load them variously for long periods of time. That is clearly impracticable on a large scale, but the tests reported in this paper reflect this positive and direct method of obtaining such results.

In 1930, V. M. Montsinger presented a comprehensive paper[1] before the Institute in which was stated the theory that the rate of deterioration of insulation in oil is doubled for each increase in temperature of eight degrees centigrade and, conversely, is reduced one-half for each decrease of eight degrees centigrade. This theory is widely accepted as trustworthy. Based upon this theory and a number of calculations of temperature under various conditions of loading, Mr. Montsinger built up a relationship between temperature and the useful life of a transformer in years. One conclusion reached was that a self-cooled transformer having an average temperature rise of 55 degrees centigrade and a maximum temperature of 105 degrees centigrade, actually operating at full load continuously in an ambient temperature of 40 degrees centigrade, would have a useful life of about seven years. Tests made on insulating materials in open oil formed the starting point for his curve of relationships and for this conclusion.

In 1934, L. C. Nichols presented a paper[2] in which a method of relating temperature and life was proposed. The

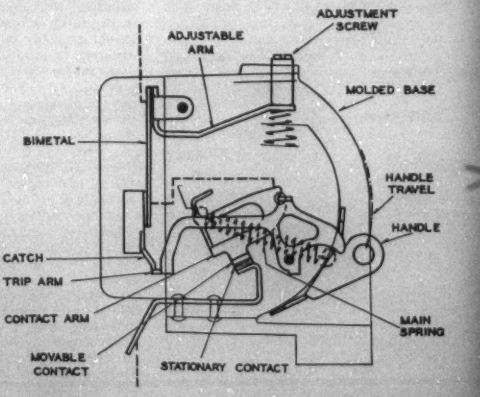

Figure 1. Schematic diagram showing the mechanism of the type "FR" thermal relay and the path of the load current through the contacts and the bimetal by dot-and-dash line

Paper number 38-122, recommended by the AIEE committees on electrical machinery and protective devices, and presented at the AIEE Southern District meeting, Miami, Fla., November 28-30, 1938, and at the AIEE winter convention, New York, N. Y., January 23-27, 1939. Manuscript submitted August 31, 1938; made available for preprinting October 20, 1938.

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1. For all numbered references, see list at end of paper.

starting point for this system was based upon a five-year test made on insulating materials in open oil at 90 degrees centigrade. This system indicated a useful life of $1^1/_2$ years for a self-cooled transformer having an average temperature rise of 55 degrees centigrade, maximum temperature of 105 degrees centigrade, and operating continuously at full load.

Systems such as these can be built up acceptably so far as relationships between different operating conditions are concerned but they are vulnerable in that they finally must be tied into fundamental time-deterioration data of unquestioned reliability obtained either from tests which correctly represent operating conditions or else from actual operating experience. The difference between 7 years and $1^1/_2$ years of useful life derived from the two systems mentioned is an illustration of the point. A comparatively small change in the starting point of either system would result in considerable change in indicated periods of useful life.

The recommendations for short-time overloading prepared by the AIEE transformer subcommittee[3] and the ASA sectional committee on transformers are based upon the eight-degree rule and upon actual experience in service, with perhaps a rather liberal interpretation of that experience. It is assumed, a little questionably perhaps, that certain relationships between maximum temperature limits and time have been demonstrated as correct because they have been used satisfactorily for many years for purposes of standardization. These time-temperature relationships are:

250 degrees centigrade for five seconds—used as a limit for short-circuit conditions

160 degrees centigrade for one minute—used for grounding transformers

95 degrees centigrade for continuous operation—this is the hottest-spot winding temperature of a 55-degree transformer operating in 30 degrees centigrade ambient

A curve drawn through these three points gives a complete relationship between temperature and useful life. It may be said of each of the three points that they perhaps have not been actually and consistently reached in average operating experience, and for that reason, they do not accurately represent actual experience. If so, they merely err on the conservative side.

Operation With Inert Gas

Temperature-deterioration data so far published have all been acquired in tests of materials in open oil with the oxygen of the air contributing a certain measure of deterioration to the materials tested. In contrast with such tests, elaborate long-time tests of coils and of the commonly used insulating materials have been made in oil protected against the harmful effects of air by means of "inertaire." As was to be expected, these tests showed that insulating materials suffer appreciably less deterioration and have longer useful life for a given temperature. In other words, they show that insulating materials in oil protected against contact with air will withstand appreciably higher temperatures than in open oil. The conclusions drawn from these carefully made tests indicate clearly that there is practically no deterioration of insulating materials at the limits of temperature suggested by the Institute and the American Standards Association.

The practical benefits accomplished with inert gas in maintaining the oil in the best possible condition and in reducing the rate of deterioration of the insulation have come to be very generally understood and appreciated. The trend in transformer practice has been toward operation with inert-gas protection or, as the next best thing, toward the use of gas-tight cases which limit the amount of air in contact with the oil and prevent the addition of more air. The best practice, except for inert-gas protection, is to make use of rugged gas-tight cases that do not allow the inbreathing of fresh air, with enough air space to limit the internal pressure to a reasonable value at the maximum operating temperature. In making cases gas-tight, the gasketing of joints between covers and tanks and at bushings and

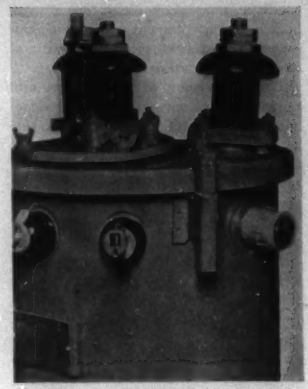


Figure 3. The indicating lamp as used with distribution transformers

When the copper temperature reaches the AIEE limit of temperature, this warning signal comes on. Even though the load decreases, the lamp remains lighted until it is reset, thereby indicating that at some time the load on the transformer reached its maximum safe value

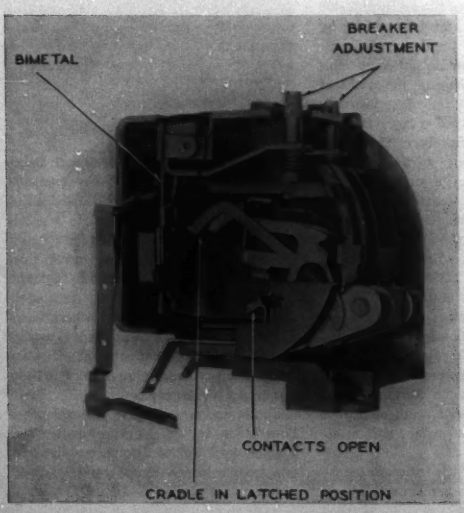


Figure 2. The type "FR" copper temperature relay showing the mechanism in the tripped position

Connected in series with the transformer winding, either directly or through a current transformer, it provides the means for overload relaying directly by copper temperature, thus permitting overloads of any size or duration until the limit of copper temperature is reached

The type "*TR*" relay, a somewhat more elaborate device, gives an advance warning light signal at a copper temperature about 30 degrees centigrade under the maximum safe temperature

handhole or manhole covers has always been a serious problem. That problem seems to be solved successfully with a new gasketing material called "corprene."

Today designers of transformers are thinking not of name-plate ratings alone but are giving careful consideration to the design of bushings, leads, tap-changers and the like, to see that they will not constitute limits which would prevent the complete utilization of whatever latent overload capacity is otherwise available.

The useful results of making transformers gas tight are perhaps not generally recognized. The practice has an appreciable effect in reducing the deterioration of oil and insulation and in giving the transformer longer life. It contributes a measure of increased latent overload capacity. It has been proved that considerable short-time overload capacity is available in distribution transformers of gas-tight construction and that it can be utilized with the method of loading by copper temperature about to be described.

Loading by Copper Temperature

The term "loading by copper temperature" has been applied to the practical utilization of short-time overload capacity which has been developed and applied to distribution transformers of the "*CSP*" type, and more recently to "*CSP*" power units. Briefly, the method consists of relaying directly by copper temperature in such a way that the transformer will carry any useful overload until its maximum safe temperature is reached before it automatically disconnects the load. Under short-circuit conditions, however, it will disconnect the load immediately.

The dividing line between useful overload range and short-circuit range is largely an arbitrary one which can be changed by adjustment of the relay. Experience shows that for distribution transformers the useful overload range should extend up to 5 or 6 times normal load, while for power transformers a range up to $3^1/_2$ to 4 times normal load proves satisfactory.

The relay which accomplishes these desirable results consists of a suitable contact mechanism actuated by a bimetal or thermostatic element which is immersed in the same oil as the winding and which carries the same current or a proportional current obtained with a current transformer. Figures 1 and 2 show a schematic diagram and a picture of the simplest type of this relay.

Figure 4. Operating handle of the relay

Used with the distribution transformer to reset the indicating lamp and breaker after tripping. The handle can also be used to open and close the breaker, a convenience during the installation of the transformer

It is shown in the appendix that the temperature of the bimetal can be made to follow the copper temperature in such a way that it always arrives at the tripping temperature whenever the copper of the winding reaches the maximum safe temperature. It is also shown that, by proper correlation of the design of the bimetal with the winding gradient, this will be true regardless of the ambient temperature. This statement applies only to the useful overload range, for the breaker trips immediately in the short-circuit range without waiting for the copper to arrive at its maximum safe temperature, as the analysis of the appendix clearly shows. The higher the short-circuit current the faster will be the tripping. The point where this immediate tripping begins can be changed at will by adjusting the relay.

The type "*TR*" relay, which is somewhat more elaborate than the simple "*FR*" type shown in figures 1 and 2, embodies an arrangement whereby a signal gives an advance warning of an approaching high-temperature condition which might cause an outage if it is allowed to continue.

In the small "*CSP*" distribution transformer, the relay element operates an internally mounted circuit breaker directly and the warning signal is an indicating lamp (see figure 3). In the case of the power transformer, the relay is connected in the control circuit of the main circuit breaker and the same warning signal is used.

Advantages of "Loading by Copper Temperature"

The simple arrangements described above can be very helpful in system operation for minimum cost and maximum service continuity. For example, consider their application to distribution transformers. Smaller units can be safely selected initially because it is not necessary to provide for future growth since there is little possibility of burnout. As loads gradually build up on certain transformers to the point where large units are required, the warning signals will automatically indicate the situation and those particular transformers can be replaced with larger sizes.

Similar advantages are realized when "operation by copper temperature" is applied to power transformer units. On one system where a number of "*CSP*" power units similar to figure 5 were in

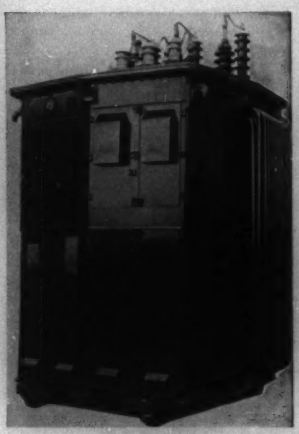


Figure 5. A 1,000-kva "CSP" power transformer

This transformer is provided with a thermal relay for operation by copper temperature. In an emergency, this transformer carried 190 per cent load for two hours, safely and without a service interruption—a good example of the practical use of latent short-time overload capacity

operation, it was necessary because of emergency repair work to maintain service, to place a 1,900-kva load on a 1,000-kva three-phase transformer. This condition existed for two hours before the load could be reduced. Toward the end of that period the warning lamp signal operated indicating an approach to a dangerous temperature, but the point of breaker operation was not reached. The load temperature curves for this unit indicated that it would be expected to carry such an overload following full-load temperatures for somewhat over two hours before tripping out on copper temperature. This illustrates clearly the value of operation by copper temperature in eliminating unnecessary service interruptions.

In establishing limits of copper temperature for the "*CSP*" transformer, the signal light is set to operate at about 95 degrees centigrade average copper temperature by resistance. This is the limit recognized in the AIEE Standards. It is the purpose to set the tripping point of the breaker as high as possible without burning out the windings in order to eliminate all but absolutely necessary interruptions due either to short circuit or to really dangerously high temperatures. For the same reason it is felt desirable to design the bimetal so that it will permit higher temperatures for short periods of time than for long periods rather than to trip at the same maximum temperature regardless of the duration. This accounts for the "hump" at about one hour in the curves of winding temperature in figure 7. To obtain this characteristic a somewhat lower bimetal resistance is used than is given by equation 7 in appendix I.

Figure 6. A 333-kva 7,200-volt single-phase transformer equipped with a thermal relay for operation by copper temperature

The maximum average temperatures reached for different overloads on a five-kva "*CSP*" transformer are shown in figure 7, together with the corresponding overloads. It will be found that for overloads of several hours duration the maximum temperature permitted is about 120 degrees centigrade, while at approximately 328 per cent load for $1\frac{1}{4}$ hours the maximum temperature is 145 degrees centigrade. For still larger loads and up to the short-circuit range, maximum temperatures are less.

Tests of the New System

If the breaker is set so that a maximum average copper temperature of 145 degrees centigrade is reached under some conditions, it would be natural to inquire if such a temperature would not damage the winding and how many times a winding could be subjected to such a temperature before failure.

To answer these questions, a program of temperature-cycle tests was started on four five-kva "*CSP*" transformers on June 1, 1936, and is still in progress. These transformers have been operated back to back in two groups, the units of the first group being designated as *A* and *B*, and in the second group as *C* and *D*. A summary of the tests is given in table I.

The procedure has been as follows: Starting at room temperature, a load of 278 per cent was applied to units *A* and *B*, and 350 per cent to units *C* and *D*. These loads were maintained until the breakers tripped on copper temperature in each case. Figure 7, which gives the characteristics of these particular transformers, shows that the 275 per cent load would trip the breaker in about two hours at average copper temperature by resistance of about 132 degrees centigrade. Similarly, the 350 per cent load would be carried about one hour and would result in an average copper temperature of approximately 145 degrees centigrade at the tripping point. These values assume an ambient temperature of 25 degrees centigrade, while during the tests the actual ambient temperature varied roughly from 17 degrees centigrade to 32 degrees centigrade during the summer and winter seasons. The durations of the overloads were correspondingly affected, but the attained copper temperatures were not measurably affected. These cycles of overload and trip-out were repeated continuously during the complete runs.

At the end of the first run, transformers *A* and *B* had been subjected to 100 cycles of operation at 275 per cent load to the tripping point, and trans-

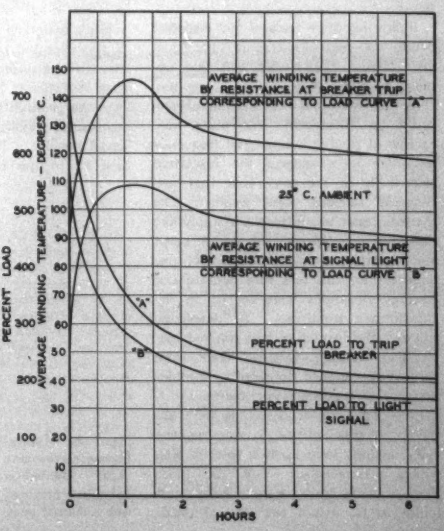


Figure 7. Typical short-time overloads for a five-kva distribution transformer

Curve *B* shows the load required to light the signal light for various time periods and curve *A* correspondingly shows the loads required to trip the breaker

formers *C* and *D* had been subjected to 100 cycles at 350 per cent load. At this point the regular AIEE dielectric tests were applied to the transformers, the dielectric strength of the oil was measured, and the breaker calibrations checked. The transformers passed their dielectric tests, the dielectric strength of the oil averaged about 30 kv, and breaker calibrations were found to be within the proper bands.

In starting the second run it was decided to increase the severity of the tests and, accordingly, the loads were increased to 390 per cent and 450 per cent, respectively. After 92 additional cycles, standard AIEE dielectric tests were successfully applied, the dielectric strength of the oil was found to average 35 kv, and a check of the breaker calibration showed that it was still in the band.

Following these tests of 192 complete cycles of high-temperature operation, an ignitron short-circuit test was applied to two units to see if any mechanical weakness in the insulation could be developed. The units were excited at double voltage and frequency in order to overstress the insulation electrically at the same time that mechanical stresses were applied. The ignitron timer was adjusted to apply five short circuits spaced six cycles apart and repeated every 15 seconds for one minute. By this test very definite and forceful vibrations were set up in the transformer windings. To determine whether the insulation had suffered mechanical damage, impulse tests were successfully applied, followed by double-voltage excitation and ratio tests.

Since no signs of weakness were detected, it was decided to continue the cyclic loading tests up to a total of 500, which was reached May 25, 1938. Breaker calibrations were checked and found to be within the original band. Dielectric strength of the oil was measured on the four units and found to be 33.7 kv, 36 kv, 34.3 kv, and 30.7 kv. The oil was reported dark red wine color and cloudy, but oil ducts were clear and temperature measurements at this point checked the original measurements. Impulse tests were repeated successfully, also the AIEE dielectric tests, including a one-minute induced test at 400 per cent of normal voltage.

The cyclic loading tests were again continued and by June 15, 1939, a total of 867 cycles will have been completed. The tests were started June 1, 1936, and, as stated before, have been run almost continuously ever since.

Table I. Summary of the 660 Cycles of Short-Time Overload Operation of Five-Kva "CSP" Distribution Transformers

Run Number	Transformers	Load (Per Cent)	Cumulative Number of Cycles	Attained Maximum Copper Temperature by Resistance (Degrees Centigrade)	Average Duration of Each Overload (Minutes)
1	*A* and *B*	275	100	132	120
2	*A* and *B*	390	192	142	48
3	*A* and *B*	390	500	142	48
4	*A* and *B*	390	660	142	48
1	*C* and *D*	350	100	145	58
2	*C* and *D*	450	192	135	34
3	*C* and *D*	450	500	135	34
4	*C* and *D*	450	660	135	34

Consequences of the Tests

Frankly, the results are surprising, in view of life tests on samples of insulating materials which have been made. It was expected that failure would take place after a comparatively few cycles of such operation. The tests seem to indicate the possibility of higher short-time temperature limits than have been believed possible. They also raise a question as to the reliability of methods heretofore used for determining maximum temperature limits. As has been stated, limiting temperatures have generally been established by testing individual samples of insulating materials over extended periods in oil under various conditions and measuring the depreciation in mechanical strength.

In view of these results, it may be in order to suggest that the proper committees of the AIEE review the whole subject of maximum temperature limits of insulating materials.

In conclusion, it can be said that transformers designed for operation by copper temperature and meeting, at least approximately, the gradient conditions set forth in equation 13 of the appendix, do possess desirable short-time overload capacity which can be used for greater economy and reliability in system operation.

The simple method of operation by copper temperature described here seems well adapted to transformers of all sizes. Present equipment has no limitations so far as size or voltage class are concerned. Operation by copper temperature does not preclude the use of relaying on ground faults, or reverse power, or of conventional reclosing practice.

The advantages of operation by copper temperature are so obvious that one might predict its almost universal use in the not distant future.

Appendix—Characteristics of a Transformer Bimetal Element Under Oil

Let

T_o = oil temperature or initial temperature of the bimetal

T_t = trip temperature of the bimetal

T = temperature attained by the bimetal at any time t

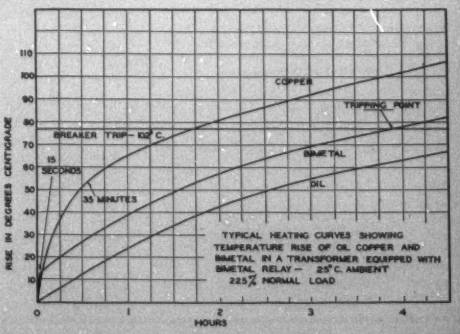

RISE IN DEGREES CENTIGRADE
HOURS
COPPER
TRIPPING POINT
BREAKER TRIP—102° C.
15 SECONDS
35 MINUTES
BIMETAL
OIL
TYPICAL HEATING CURVES SHOWING TEMPERATURE RISE OF OIL, COPPER AND BIMETAL IN A TRANSFORMER EQUIPPED WITH BIMETAL RELAY — 25°C. AMBIENT 225% NORMAL LOAD

Figure 8. Typical heating curves for a "CSP" distribution transformer provided with a thermal relay

T_{oL} = oil temperature corresponding to load L

T_{RoL} = oil temperature rise corresponding to T_{oL}

I = current through the bimetal

I_n = normal full load current

L = steady-state load required to give the maximum desired hot-spot copper temperature

W = watts input to the bimetal

R = total resistance of the bimetal

N = number of times full-load current required to produce immediate tripping

p = specific heat of the bimetal—watt seconds per gram per degree centigrade

m = mass of bimetal in grams

q = coefficient of heat convection of the bimetal in watts per square centimeter per degree centigrade

a = area of the bimetal in square centimeters

Q = aq = watts dissipated from bimetal per degree centigrade gradient

t = time period

If a current is suddenly caused to circulate through a bimetal immersed in oil at temperature T_o, the I^2R loss will partly heat the bimetal and partly be lost to the oil. Thus

$$Wt = pm(T - T_o) + \int_0^t (T - T_o)aq\,dt \quad (1)$$

Differentiating with respect to t gives:

$$\frac{dT}{dt} + \frac{aq}{pm}T = \left(\frac{W}{pm} + \frac{aq}{pm}T_o\right) \quad (2)$$

which is the differential equation for the temperature of the bimetal as a function of time. In solving this equation for an actual transformer it can be assumed that the oil temperature is constant since the bimetal transient is very rapid and will have disappeared entirely before there is any substantial change in the oil temperature.

The solution of this equation is easily shown to be

$$T = T_o + \frac{W}{aq}\left(1 - \epsilon^{-\frac{aq}{pm}t}\right) \quad (3)$$

In figure 8, heating curves are shown for an actual transformer. The sudden rise in the temperature of the bimetal near $t = 0$ is the transient given by equation 3.

As soon as the transient is over, that is, for large values of t, the temperature of the bimetal is given by

$$T = T_o + \frac{W}{aq} \quad (4)$$

and further increase in the bimetal temperature results only from the gradual rise in the oil temperature as can be seen from the curves of figure 9. It is apparent, therefore, that considerable time will ordinarily elapse before the bimetal attains the tripping temperature or the temperature at which it unlatches the breaker—the time being determined by that required for the oil to heat up.

However, it is apparent from equations 3 and 4 that if W is very large, as in the case of a short circuit, the temperature which the bimetal would attain almost immediately from equation 3 could be high enough to unlatch the breaker without waiting for the oil to heat up. Or

$T_o + \frac{W}{aq}$ could equal T_t

if W were sufficiently great.

The load or current at which this immediate tripping begins can be established arbitrarily by the proper selection of the bimetal resistance. The range during which immediate tripping takes place is designated here as the short-circuit range, while the range during which the tripping time is dependent on the heating of the oil is designated as the useful overload range.

Equation 3 is necessary for the calculation of the tripping characteristic of the bimetal relay in the short-circuit range.

Experience has taught that the useful overload range for distribution transformers should extend up to five to seven times normal current since transformers may be subjected to currents of this order due to motor starting or similar short-time overloads. In other words, N should be between five and seven. To bring about immediate tripping at any particular value of N, the bimetal resistance can be determined as follows:

$$T_t = T_o + \frac{N^2 I_n^2 R}{aq_1} \quad (5)$$

But under steady-state conditions the trip temperature must be reached at load L. Hence

$$T_t = T_{oL} + \frac{L^2 I_n^2 R}{aq_2} \quad (6)$$

q is not quite constant because the oil convection increases with increased oil temperature. q_1 is therefore used in equation 5 and is determined for T_o while q_2 in equation 6 is determined for oil temperature T_{oL}.

Equating (5) and (6) and solving for R gives

$$R = \frac{Q_1 T_{RoL}}{I_n^2\left(N^2 - \frac{Q_1}{Q_2}L^2\right)} \quad (7)$$

where

$Q_1 = aq_1$

which is the bimetal resistance required to give a useful overload range up to load N and immediate tripping above N.

A highly desirable characteristic of the bimetal relay is that it compensates automatically for changes in ambient temperature permitting higher loads at low temperatures and less load at high temperatures in accordance with the thermal capability of the transformer. Obviously this comes about if the bimetal trips the breaker at the same maximum copper temperature regardless of ambient temperature. To bring this about the winding gradient must fulfill a condition determined as follows:

As the permissible steady-state load L changes with ambient temperature, if the bimetal trip temperature is to be reached at the same maximum copper temperature, then any increase in the bimetal gradient (W/aq) with increasing load must be offset by a corresponding decrease in the oil temperature with increasing load—or

$$\frac{dT_{oL}}{dL} = \frac{-dW}{dLaq} \quad (8)$$

But

$$W = L^2 I_n^2 R \quad (9)$$

$$\frac{dT_{oL}}{dL} = \frac{-2LI_n^2 R}{aq_2} \quad (10)$$

But the transformer characteristics determine the relation between oil temperature and the maximum permissible steady load and varying ambient from which dT_{oL}/dL must be evaluated.

In general

$$T_{oL} = T_c - KL^x \quad (11)$$

where

T_c is the copper temperature corresponding to load L

KL^x = gradient

Usually x ranges from 1.5 to 2, but the heating curves of the transformer determine the exact value to use.

Differentiating (11) at constant T_c gives

$$\frac{dT_{oL}}{dL} = -xKL^{x-1} \text{ or } = -2KL \text{ (for } x = 2) \quad (12)$$

Equating (10) and (12) and solving for K gives

$$K = \frac{I_n^2 R}{aq_2} \quad (13)$$

which is the gradient coefficient required for ambient temperature compensation, the value of R having been obtained from equation 7.

The gradient required by equation 13 will be found quite low, and if it cannot be obtained it may be desirable to change the bimetal resistance to give ambient temperature compensation with the K which can be obtained. In this case

$$R = \frac{KQ_2}{I_n^2} \quad (14)$$

and the maximum overload before immediate tripping would be

$$N = \sqrt{\frac{Q_1}{Q_2}\left(L^2 + \frac{T_{RoL}}{K}\right)} \quad (15)$$

which is obtained by substituting (14) in (7) and solving for N.

References

1. Loading Transformers by Temperature, V. M. Montsinger. AIEE Transactions, volume 49, April 1930, page 776.

2. Effect of Overloads on Transformer Life, L. C. Nichols. AIEE Transactions, volume 53, 1934, page 1616.

3. Operating Transformers by Temperature, W. M. Dann. AIEE Transactions, volume 49, April 1930, page 793.

Discussion

F. M. Starr (General Electric Company, Schenectady, N. Y.): This paper is of considerable interest and importance because it presents new data on the ability of transformers, particularly of the distribution class to carry heavy overloads. Considerable has been written in recent years as to the proper thermal overloads which should be tolerated in transformers. Conclusions reached vary widely in degree, but in principle they are all in agreement that repeated overloads reduce transformer life and that there is a threshold of loading beyond which the reduction in transformer life is so pronounced as to make such overloads extremely uneconomical. This point of view limits its economics pretty largely to the life and cost of a transformer.

The distribution engineer must necessarily have a broader point of view since his problem is somewhat greater than getting the maximum possible usage out of his equipment. It is his job to design a distribution system to deliver a kilowatt-hour to the consumer within specified criteria of voltage regulation and service continuity at the lowest possible cost. In making his broad economic analysis to this end he finds that energy losses and voltage drop in the transformer and perhaps even revenue are just as important factors in determining the loading of a transformer as its thermal capacity. For example it has been found in certain localities that the most economical design of secondary networks, considering voltage regulation and energy losses as contributing factors, results in transformer loading of only 75 per cent of name-plate capacity.

The reaction of the distribution engineer to the conclusions in this paper is likely to be that he is getting and paying for thermal capacity in transformers that he cannot possibly use because of excessive voltage drops or transformer losses. He might justifiably ask, "Why not sacrifice some of this thermal capacity and give me a lower cost transformer or a lower impedance transformer." Because of basic design limitations it is difficult to obtain what might be called an ideally balanced design of transformer for the economic distribution system. There has been considerable progress in this direction, however. It seems to me important and significant that if a more perfectly balanced design of transformer embodying maximum economy as well as the desirable operating characteristics is to be attained in the future, distribution engineers must not impair such progress by specifying unusable and unnecessary thermal capacities which have characterized some designs of the past.

J. H. Christensen and **J. P. Hamilton** (both of Tennessee Valley Authority, Wilson Dam, Ala.): The temperature-cycle tests described by the authors were made to determine whether or not a maximum average copper temperature of 145 degrees centigrade would harm the winding insulation. The transformers subjected to this test were of the five-kva "*CSP*" type. The authors have shown that these tests, which were made continuously over a period of two years without an insulation failure, indicate that the present maximum copper temperature of 105 degrees centigrade may be entirely too low. If so, transformers of higher ratings could be designed with only slightly increased costs, provided the relays under discussion give satisfactory operation under field conditions.

In this connection, a question arises concerning the practical application of this relay, namely, what provision is proposed to facilitate the adjustment, maintenance, or replacement of these units in large power transformers.

The outstanding feature of this work is the novel means used to obtain, with safety, the fullest utilization of conventional insulation in transformers. It is interesting to note the similarity in the design and application of this feature to that of the type "H" Sentinel breaker used for small-motor overload protection.

W. C. Sealey (Allis-Chalmers Manufacturing Company, Milwaukee, Wis.): The tests described in this paper show that a modern transformer will stand a great amount of abuse without actually failing. The previous tests and experience on the deterioration of insulating materials due to time and temperature are not challenged by the results of the tests. Very high overloads have been carried and the transformer has been able to operate successfully after being subjected to the high temperatures obtained. However, it has been demonstrated by these tests that the oil and insulation are not in first-class condition because of the high temperatures to which they were subjected. The case is a good deal like that of automobile tires. There are tires in operation in which the tread has worn smooth and even tires in which the fabric is showing. These tires operate successfully, but, if reliability and safety of service is a factor, they cannot be considered to be in satisfactory operating condition.

These tests show that even with insulation in poor condition the transformers may still operate successfully. Since the oil deterioration was considerable for these tests and the insulation next to the copper must have been at a considerably higher temperature than the oil temperature, there is little doubt that the insulation had been damaged.

The attempt to set up certain definite safe temperatures for transformers is fundamentally difficult because there is no such thing as a safe temperature unless the time element and the permissible damage is also considered. Reliability of service is generally a first consideration, so much so that it may be desirable to work the transformer up to the absolute limit of failure before allowing service interruption. Any protective device which is put in for the purpose not of insuring continuity of service but for the purpose of protecting the transformer must reduce the total load which can be carried by a transformer without service interruption, otherwise no protection for the transformer is obtained. If the protection is set so high as to allow considerable damage to the transformer insulation, it may be well to omit the protection and allow more damage to the transformer insulation. The particular amount of damage which can be allowed before the transformer is tripped off is different for different applications but, in general, the best continuity of service is obtained by protecting the transformer only against real short circuits and not for overloads caused by useful load on the system.

It has been found that thermal devices which protect the transformer for the generally considered safe operating temperatures provide undesirable service interruptions. The next natural step is to either omit the thermal device or to operate the thermal device with a less margin between its point of operation and the actual point of failure of the transformer and so that the point of operation of the thermal device exceeds generally accepted safe temperatures for the transformer. If it is necessary to raise the level of protection to such a point that considerable damage is done to the transformer before the device operates, it is questionable whether the device provides useful protection to the transformer. Proof that the transformer will still operate does not constitute proof that the transformer is in a safe operating condition. Transformers should be so operated that the insulation remains in good condition unless an emergency condition arises where it is necessary to damage the transformer in order to secure continuity of service. In order that transformer insulation remain in first-class condition, the normal loading of transformers should be such that serious damage to the insulation does not occur. Overloads which damage the insulation should be on a strictly emergency basis. For service continuity it seems self-evident that if all transformers on the system have their insulation maintained in good condition the service continuity will be better than if some of the transformers on the system are so operated as to have damaged insulation even if they do continue to operate. A device which offers protection only after considerable damage has been done may be desirable but it should be recognized that such a device offers very little protection against damage to the transformer and may leave the transformer in an unsafe operating condition.

R. B. George (Tennessee Valley Authority, Norris, Tenn.): During some tests which I made to determine the short-time temperature limits of transformer insulation, I recognized that there was a good margin which could be used for short time overloads if the proper precautions were taken to protect the oil from oxidation and provisions were made to remove the load from the transformer when the magnitude or duration of overload reached limits which would injure the transformer.

The paper by Mr. Putman and Mr. Dann describes tests that were made to determine these limits. A device has been proposed to disconnect the transformer from the circuit when these limits are reached.

It is suggested that the proper committees of the AIEE review the subject of maximum temperature limits of insulating materials. It is always desirable to bring the AIEE rules up to date to include new developments in the art.

The results reported in this paper have an application for electric heating loads, particularly in the southern states. There are parts of this region where electric heating would be required for a short portion of the year.

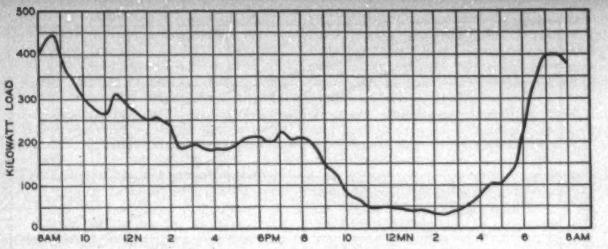


Figure 1

This load may be more economically served by using transformers with nominal kilovolt-ampere rating much lower than the peak load during the heating demand, and operating by copper temperature because electric heating is required only when the ambient temperature is low. The peak demand for electric heating usually occurs early in the morning and tapers off before the electric range load for noon cooking builds up its small peak.

Figure 1 of this discussion is a 24-hour curve of the total load on a circuit which serves 40 houses which are equipped with electric refrigerators, ranges, water heaters, and the usual appliances in addition to being electrically heated. The 17-hour average temperature from 6 a.m. to 10 p.m. was 19.9 degrees Fahrenheit. The 24-hour average temperature was 18 degrees Fahrenheit. This curve has the load characteristics which were described above. Since this curve also gives information concerning the duty on transformers for this type of load, it may be useful to a committee for reviewing the subject of maximum temperature limits of transformer insulation. Loads of this type can certainly be served more economically by taking advantage of operating by copper temperature during the peak loads which occur only at low ambient temperature.

A. C. Monteith (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The two outstanding factors brought out in this paper are the greater overload capacity of a transformer when the oil is kept free from contact with air and the fact that a reliable device is available to allow taking full advantage of this overload capacity without fear of burnout. Where regulation is not the determining factor in the transformer application, this overload capacity should allow fitting the transformer more closely to the load, thus allowing a reduction in initial investment. Since the "*CSP*" power transformer is equipped with step-type regulators, heating becomes the main factor in applying the transformer.

A secondary network system is designed so that the transformers will be called on to carry full load with one feeder out of service and carry some overload with two feeders out of service. Regulation is usually not a problem in this type of system, so that taking full advantage of a transformer having a tight tank and increased overload capacity should allow reducing the ratio of installed transformer capacity to full load. This is particularly true where networks are installed for supplying the lighter-load areas, as a greater chance can be taken as compared to the application for the heavy-load areas. Quite often the overload capacity given in the paper would allow carrying certain types of loads through the peak, which would mean applying the transformers based on their overload capacity rather than the continuous rating. Such factors should allow extending the economical use of the secondary network system.

The use of the thermal trip device applied to network transformers also presents a method of protecting against burnout in case of prolonged overload. Considerable time has been spent in trying to design a fuse that will leave the transformer on the system up to the danger point. The thermal device described in the paper will give this protection, the closing of its contacts tripping the network protector. If this type of protection is adopted, consideration could be given to eliminating the fuses from the network protectors.

These are a few of the changes in application that have occurred to the writer, if advantage is taken of the data presented in the paper. The new thought presented should go far to revolutionize our approach to the distribution problem.

T. H. Mawson (The Commonwealth and Southern Corporation, Birmingham, Ala.): The paper by Messrs. Putman and Dann is undoubtedly a valuable contribution to transformer operation. Previous studies by Nichols, Montsinger, Dann, and others have substantiated the operator's belief that transformers could be operated successfully without major reduction of life at ratings in excess of that shown on the name plate. In other words, the nameplate rating was only one point on the operating curve of the particular transformer.

It is, indeed, gratifying to know that the American Standards Association has prepared a "Guide for Loading Oil Immersed Distribution and Power Transformers," following the work of these men.

Since there are no satisfactory figures available on the life of transformer insulation due to the mass of test data, as yet unavailable, required for any sort of comprehensive averages, it is difficult to determine an actual life span for any transformer. The various methods mentioned for increasing the life of the transformer insulation such as inert gas in contact with the oil, reduced area of air contacting the oil, etc., play a part, but the oil temperatures, if allowed to remain at high levels for prolonged intervals must ultimately impair the condition of the transformer.

Loading to the limits set up in the ASA standards appears conservative in view of the test data in the present paper. While the test conditions for the five-kva transformers were unusually severe, how can the conclusions drawn from the tests be interpreted in terms of actual service conditions?

If transformers are to be installed on a basis of continuous and satisfactory service, the maximum use can be obtained from a given bank when the load curve is such as to permit overloading during peak hours to the point where the maximum temperature will not cause excessive deterioration. At the same time the possibility of excessive regulation in the transformer must be considered. Since this peak load would be considered as recurrent and not an infrequent emergency, the regulation in the transformer that would occur at these peaks would tend to be excessive. If this type of loading is to be considered for future installations then the design of the system components will have to be adjusted to operate within satisfactory voltage levels.

The use of some device to determine with reasonable accuracy the "hot-spot" temperature would give data that could be used in conjunction with typical load curves for various areas. This would provide a better method of determining the best size of transformer at that location, as well as the behavior of a particular transformer.

There is again the question of transformers now in service. Lack of knowledge as to the past history of these transformers would tend to raise questions as to the remaining life. Yet every effort should be made to work these transformers to their service limit—be it kilovolt-amperes or voltage drop.

The use of a lockout device for protection would be satisfactory, provided there was some control of the load, or that there was no great time lag between operation and reclosure. Therefore, operation of transformers at levels close to the limit would tend to increase the number of interruptions from this cause.

It would seem advisable to select transformers for both power and distribution service on a basis of the guide as set up by ASA, adjusting this selection where load data warrants, rather than depend entirely upon inspection of signal-light operation.

W. R. Brownlee (The Tennessee Electric Power Company, Chattanooga): Methods of securing maximum use of capital equipment as a means of reducing the over-all cost of electric power are of most vital interest to operating companies, to manufacturers, and to the entire industry. Contributions to such methods applied to distribution transformers are of particular value at this time.

For transformers of small size and value the bimetallic relay should find a most wide application, since it is a reasonably good device and can be secured at relatively low cost. They are much superior to fuses both in available characteristics and in reasonable adherence to predetermined

curves. I wonder if the authors are advocating the use of such devices for larger and more expensive transformers whereas, many operating companies have for years made use of more reliable (and more expensive) devices such as thermocouples or calibrated resistance units for operating power transformers by copper temperature. Sometimes these devices are permitted to trip breakers but particularly in case of the larger units they provide a graphic record of temperature, permitting the system operator to exercise his judgment in balancing the probable shortening of life of the transformer unit due to the overheating, against the seriousness of the effect on service or on other equipment involved in taking the unit out of service.

Apparently the authors have relied on dielectric tests to determine whether the transformers under test suffered any damage due to overloads. Have they actually taken any of the tested units apart to determine the exact condition of the inside insulation? If such critical examination should confirm their preliminary findings, then it might be in order for the proper AIEE committees to review the subject of maximum safe temperature limits.

Probably the authors intended to include power transformers with conservators along with transformers equipped with "inertaire" equipment in contrasting the effects of over-temperature of materials tested in open oil and deterioration in oil protected from open air. Naturally gas-tight cases are preferred for small distribution transformers or for any underground installation.

V. M. Montsinger (General Electric Company, Pittsfield, Mass.): The authors have added a real contribution to the art of loading transformers by temperature under various service conditions.

There are, however, some statements made in the paper to which I must take exception. The paper states that the signal light is set to operate at about 95 degrees centigrade (permitting continuous operation at 95 degrees average copper temperature) which limit they say is recognized in the AIEE Standards. This is correct, but it has generally been agreed by the industry for the past three or four years that for continuous operation the average temperature should not exceed 85 degrees or 55 degrees rise in a 30-degree ambient. They may intend that the 95-degree average temperature limit be used only for short-time operation. If so, what is there to prevent the transformers operating continuously at average copper temperatures close to 95 degrees centigrade? This point is not clear.

As a matter of fact, AIEE Standards No. 13 will be superseded within a few months by the Proposed American Standards and Recommended Practices for Transformers, which recommend that for continuous operation the average copper temperature not exceed 85 degrees centigrade.

If the conditions are such as to permit continuous operation at 95 degrees average temperature by the signal light, I would like to suggest that the authors either recommend the temperature limit of 85 degrees centigrade as given in the new guides for operation of transformers, which are a part of the proposed American standards mentioned above, or give a valid reason for (or data to support) setting the temperature limit ten degrees higher than recommended for continuous operation in the proposed guides.

The authors make the statement that when the oil is protected against the harmful effects of oxygen by "inertaire," there is practically no deterioration of the insulating materials at the limits of temperature suggested by the Institute and the American Standards Association. I think the authors should state whether they mean the Institute or ASA since, as stated above, the temperature limit recommended by ASA is ten degrees lower than that recommended by the Institute.

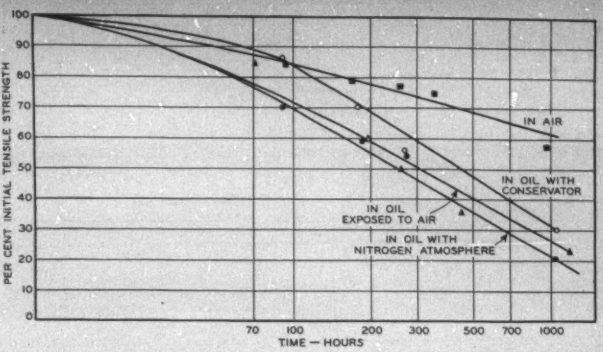


Figure 3. Aging of class A insulations at 105 degrees centigrade

Materials used: (1) 0.031-inch pressboard, (2) 0.010-inch kraft paper

Tests made in 1935

The authors state that all aging tests of class *A* insulations in the past have been made in oil exposed to air and by inference say that most, if not practically all, of the aging of insulation in oil at 95 degrees average temperature (with the hottest spot ranging from say 98 to 105 degrees depending on the design) is due to the presence of oxygen in the oil. This does not agree with what I have found.

In 1935 our laboratory made two separate series of aging tests to determine the difference in the aging (tensile strength) of various class *A* materials immersed (1) in air, (2) in oil exposed to the air, (3) in oil with a nitrogen atmosphere, and (4) the oil protected by a conservator.

Both untreated and treated materials were tested. The treated samples were given a 30-minute varnish dip, centrifuged to remove excess varnish, and baked to set up the varnish. The materials were cut into pieces approximately ten inches square and then assembled in packs, part of the materials being spaced with pressboard spacing strips to allow circulation of the oil or air, and the remaining materials assembled in a tightly-packed mass.

The test conditions were made to represent as nearly as possible the conditions of transformers in service.

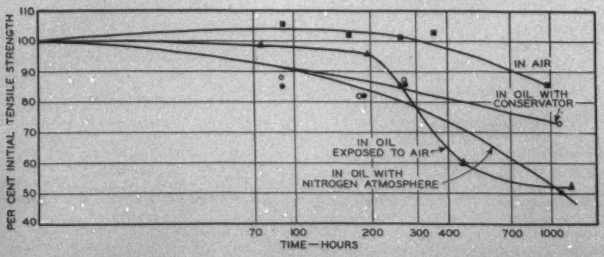
The materials which were aged in oil were immersed in oil in steel containers and placed in an oven maintained at a constant temperature of 105 degrees centigrade plus or minus one degree.

In the case of aging in oil with conservator, the connecting pipe flush with the cover was connected to the conservator on the outside of the oven.

The tank with the nitrogen atmosphere was connected to a bomb of oxygen-free nitrogen through a pipe leading to the bottom of the tank. Another pipe flush with the cover was connected to a pressure release valve set to a pressure of one-half pound. After the insulation and oil were placed in the tank, the oil being at a level

Figure 2. Aging of 0.031-inch pressboard at 105 degrees centigrade

Tests made in 1935



of about two inches below the cover, nitrogen was flushed through the oil for a period of one hour, then the nitrogen was shut off, and the aging started. Each time the tank was opened to remove samples, the air was thoroughly flushed from the oil with nitrogen before resuming the test.

The container in which the material was aged under oil with air over the oil was an open tank.

The aging in air was accomplished by placing bundles of the insulation in an oven maintained at a constant temperature of 105 degrees plus or minus 1 degree centigrade, taking care to keep the material from contact with metal in the oven.

All samples were conditioned in a standard atmosphere four hours before testing. A set of standard samples was immersed in the aging medium one hour at room temperature, conditioned four hours under standard humidity conditions, and tested to obtain standard data for the aging comparison.

The results of the aging tests are shown in figures 2 and 3 of this discussion which indicate:

1. That insulation aged in air has a longer life than insulation aged in oil.

2. That insulation aged in oil plus air, or in oil plus conservator, or in oil plus nitrogen atmosphere, shows approximately the same amount of mechanical deterioration.

There was practically no difference between the rate of aging of the materials spaced or unspaced in oil. In air, the spaced materials showed approximately ten per cent less aging.

The authors state that to determine whether the heavy overloads had injured the transformer, AIEE dielectric tests were applied. I do not feel that these tests mean anything, since insulation can be greatly weakened mechanically before its dielectric strength is affected. In fact, the dielectric strength of oil-immersed insulation does not decrease until it is well carbonized and cracked. I note that a few short-circuit tests were made, which were probably a better test on the insulations than the dielectric tests.

I would like to suggest that a better method of determining the effect of short-time overloads on the insulation would be to integrate the heating curve area in some such manner as I used in my AIEE paper entitled "Temperature Limits for Short-Time Overloads for Oil-Immersed Neutral-Grounding Reactors and Transformers" published in AIEE TRANSACTIONS, volume 57, 1938, pages 39–44 (January section). This method of analysis ought to give some idea of whether 500 or 600 load cycles has appreciably weakened mechanically the insulation.

H. V. Putman and W. M. Dann: The discussions on the paper "Loading Transformers by Copper Temperature" have brought out a lively interest in the subject. The purpose of the paper was to give emphasis to the recognized fact that transformers inherently have a substantial overload capacity for short-time periods and to describe a practical way of taking advantage of this capacity automatically in service. The prevailing views of those who discussed the paper seem to be that the utilization of this short-time overload capacity is of vital importance to the operating companies and to the industry in general and that in the main the method of obtaining its full utilization is effective and practical.

Messrs. Christensen, Hamilton, George, and Brownlee suggest either that the AIEE temperature limit of 105 degrees centigrade may be too low or that perhaps the Institute should review the subject of limiting temperatures. As pointed out in the paper, we believe these suggestions should be carried out, particularly in connection with limiting temperatures for short time periods.

Mr. Mawson speaks of the "Guide for Operation of Transformers," which is about to be published by the ASA, and comments that it would seem advisable to select transformers on the basis of this guide rather than to rely entirely upon signal-light operation. However, the overloads suggested by the ASA guide are quite conservative; they had to be because they apply to transformers of more than one type and to units that have been in service for the past ten years. Modern transformers operated by copper temperature with the relay and signal device will, of course, carry the short-time overloads of the ASA guide, but they will go further; the signal light will give a warning when a definitely established temperature is reached and will cut the transformer out if the operation is continued until a temperature is reached at which appreciable shortening of life would result. Furthermore, ambient temperature is automatically taken into account and it is unnecessary to consult tables of permissible overloads.

Mr. Montsinger points out that the signal light is set to operate at about 95 degree centigrade and he asks whether there is anything to prevent operating a transformer continuously at an average copper temperature close to 95 degrees centigrade. It is a fact that the transformer, just like an ordinary unit, could be artificially loaded so that its temperature rise plus the ambient temperature would be continuously just inside the limit of signal operation and its average winding temperature would be continuously close to 95 degrees centigrade. But it is hardly conceivable that a transformer would be called upon to carry its full load continuously in actual service with an ambient temperature which is continuously 40 degrees centigrade. Load conditions and ambient temperatures in actual service are largely uncontrollable; they normally vary throughout the day and the season, and in cases where a transformer is so small with regard to its load conditions that its average copper temperature occasionally reaches 95 degrees centigrade or thereabouts, it seems obvious that it would be better to know of the conditions through signal-light operation than to be unaware of them. A very natural question arising from Mr. Montsinger's inquiry is—what is there to prevent *any* distribution transformer from operating continuously at 95 degrees centigrade?

Mr. Mawson asks how the conclusions drawn from the tests on the five-kva transformers may be interpreted in terms of actual service conditions. It is not possible in a laboratory to simulate a large number of the overload conditions that can exist in actual service, but the tests do represent very severe cases of certain types of overload, and operation at other overloads in service may be sized up by analysis and comparison.

Mr. Mawson speaks of the life span of transformer insulation, having in mind the effect of temperature, while Mr. Starr reminds us that repeated overloads reduce transformer life and that there is a threshold of loading beyond which overloads are uneconomical. Mr. Sealey introduces a striking comparison to automobile tires and says that the oil and insulation in the transformers under test are not in first-class condition because of the high temperatures to which they have been subjected. It is of course too early to say what the condition of the insulation actually is, but there is nothing in the tests themselves to indicate that the oil and insulation have been seriously damaged. At the time the paper was written, after 660 cycles of severe overloading, the transformers had more than once withstood the standard AIEE low-frequency and impulse tests and the oil, while darkened in color, had withstood even higher breakdown tests than before the cycle tests were started. These dielectric tests and the fact that the transformers are still going through similar cycles of tests indicate that they are still good for actual service.

Mr. Montsinger questions whether the successful application of Institute tests means anything, and he points out that insulation can be greatly weakened mechanically before its dielectric strength is affected. That was the very reason for subjecting the transformers to a series of short-circuit tests with an ignitron timer. The violent vibrations of those tests failed to develop any mechanical weakness of the insulation, for the transformers immediately afterward withstood impulse tests and tests at double-voltage excitation. When the cycle tests are finally discontinued the units will be dismantled and the insulation minutely examined. The results of this examination will no doubt form a contribution to the study of the life of transformer insulation.

Mr. Brownlee asks whether the relay and signal devices are advocated for large transformers, and Messrs. Christensen and Hamilton raise the question of adjustment, maintenance, and replacement of the devices in large power transformers. These devices are right now being used in service with complete satisfaction on transformers as large as 1,500 kva. They can be used effectively for power transformers of any size. A convenient adjustment of the relay is provided for, but field experience with more than 200,000 "transformer-years" in service indicates that adjustment has not been necessary and that maintenance attention will be rarely needed. If a relay were to fail it would have to be replaced.

Mr. Monteith comments on the considerable time that has been spent in trying to design a fuse that will leave the transformer on the system up to the danger point, and he points out the value of the relay for this kind of protection, while Mr. Brownlee remarks that the relay is much superior to the fuse.

Mr. George speaks of the early morning peaks caused by electric heating loads. This is an excellent illustration of a peak that can be taken care of with transformers having ratings much lower than the peak

Effects of Temperature on Mechanical Performance of Rotating Electrical Machinery

C. LYNN
ASSOCIATE AIEE

THE EFFECTS of temperature on electrical machinery are usually considered in connection with the deterioration of insulation used on the active conductors themselves. There are, however, many other parts of these machines where temperature effects are important and vitally affect the design of the machine. Unless provision is made in the design of machines to take care of these effects, unsatisfactory operation or reduced life may result. These effects on machine construction may be considered in three groups.

1. Effects of Temperature on Insulating Parts

Machines with class *A* insulation on the windings have class *A* materials on other parts of the machine as well as on the windings proper. On d-c machines, fullerboard insulation is used around the main and commutating poles to give ground insulation and creepage to ground. On a-c salient-pole machines, fullerboard or fish paper is commonly used for a similar purpose on the rotor poles. Where higher temperature rises than those permitted for class *A* materials are encountered, these materials must be abandoned in favor of class *B* materials such as asbestos, mica, or woven-glass formed shields. To eliminate formed channels and insulating pieces around the stationary pole pieces, railway motors and other propulsion equipment requiring maximum output with minimum space and weight have the necessary insulation protection to ground incorporated in the coil insulation itself. Mummified coils using class *B* conductor insulation are provided with sufficient mica or asbestos insulation on the outside of the coil itself to give normal protection to ground.

If temperature limits are pushed very high, such machines as enclosed self-ventilated motors would get extremely high temperatures on all internal parts and fibrous materials, such as used for insulation between brush holder brackets and rocker rings, would no longer be satisfactory, and special porcelains or molded mica materials as used on railway motors for brush-holder-stud insulation would have to be used.

On both a-c and d-c machines, fish-paper cells of class *A* material are used in the slots, not from an insulation standpoint but to provide, during winding, protection to the coil sides against the edges of the laminations in the slots. With higher temperatures such cells are abandoned or mica cells can be substituted.

Wedges for class *A* machines are universally made of fiber. Excessive temperatures cause such materials to soften, shrink, and sometimes split or crack. When wedges become loose or crack, they generally work endwise out of the slots, although sometimes they push radially out of the slots, especially near the ends of the core. Substitutes of Micarta or other phenolic base materials may be used. High temperatures are also detrimental to the fiber winding strips that are used under the wedges to provide a sliding base for the wedge when being driven in the slot grooves and to provide a means of securing a tight coil in the slot. Mica-base material must then be substituted.

All d-c machines, wound-rotor induction motors, and rotating-armature a-c machines use bands of wire to hold the end windings of the rotors in position. On almost all except the smallest machines, coil supports are used under the end windings and the coils are held down against these coil supports on the end portion. Channel or other types of insulating material are used on the coil supports to provide insulation and creepage to ground. Layers of insulating material and fullerboard are placed around the armature coils on the ends to provide insulation and protection to the coils from the steel band wire which holds the end windings in place. High operating temperatures cause this insulating material, as well as the insulation on the coil supports, to shrink and thus the coils and bands will become loose on the end windings, unless special materials and precau-

Paper number 39-17, recommended by the AIEE committee on electrical machinery, and presented at the AIEE winter convention, New York, N. Y., January 23-27, 1939. Manuscript submitted November 22, 1938; made available for preprinting December 8, 1938.

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load, when loaded by copper temperature with the relay and the signal device.

The results of Mr. Montsinger's tests extended over a period of only about 40 days, which is hardly sufficient to give reliable conclusions. To state it simply, Mr. Montsinger's conclusions are that cellulose insulating materials immersed in new transformer oil at 105 degrees and fully protected against oxidation and moisture deteriorate just as rapidly as when the oil is subjected to oxidation and moisture by exposure to the atmosphere. This conclusion does not agree with the findings of our own research engineers and the results obtained by others, notably Stager (*Elektrotechnische Isoliermaterialien*, Stuttgart, 1931).

In a paper "Temperature Limits Set by Oil and Cellulose Insulation" by Doctor C. F. Hill (AIEE TRANSACTIONS, volume 58, 1939, pages 484–91) it is shown by carefully conducted tests extending over a period of approximately 650 days, that the deterioration of cellulose materials eventually flattens out and ceases, but that it takes more than 40 days to reach this condition. His tests show that electrically such materials maintain their initial characteristics even when above 100 degrees centigrade and they may even show improvement; this is true up to 140 degrees centigrade when the materials and oil are protected with an inert gas. Mechanically, untreated cellulose in air deteriorates rapidly above 100 degrees centigrade, or at 95 degrees centigrade when the oil is exposed to air. However, his opinion is that many transformers are operating satisfactorily in service in which the insulating materials have deteriorated to one-fourth of their original mechanical strength.

The conclusions drawn from Doctor Hill's tests are that the deterioration of insulating materials is greatest when the oil is exposed to air, and least when it is protected by an inert gas. Mr. Montsinger's tests show that the deterioration of pressboard mechanically at the end of about 40 days at 105 degrees centigrade is about the same as in oil exposed to air and in oil protected by nitrogen. This is not thought to be the case and it is not substantiated by Doctor Hill's tests. Mr. Montsinger's tests also show considerably less deterioration in oil with a conservator than in oil protected with nitrogen. It is probable that in the conservator tests there was no breathing of air and the results obtained were really due to a tightly sealed tank, which is the case with the transformers discussed in the paper on "Loading Transformers by Copper Temperature."

tions are taken to eliminate this shrinkage of the insulating materials.

Successful operation of commutators depends more on their ability to go through a temperature cycle than upon any one other feature. By this is meant their ability to keep a smooth surface, and not have bar to bar roughness with an increase in temperature. Eccentricity of commutators up to 0.001 of an inch even on high-speed machines will not affect the operation, but bar-to-bar roughness or unevenness of greater than 0.0001 inch will usually cause sparking and commutation trouble. Obviously for a given commutator, the less the temperature range the less chance there will be for bar-to-bar roughness. This does not mean that commutators should not operate at fairly high temperatures, nor does it mean that commutators should be specified to operate at excessively low temperatures.

The temperature resulting on a commutator is dependent upon the losses occurring at the commutator, the brush contact I^2R loss, and the brush friction. The I^2R loss of the current flowing in the commutator bars to the brushes is insignificant and never measured nor considered due to the large cross-section area of the commutator bars themselves and because the current flows in the bars only during the short time they pass under the brushes, during the commutation period. The loss at the brush contact due to the voltage drop of the current in passing between the commutator and brushes does vary somewhat with the material of the brush and is dependent upon the surface condition of the commutator. However, for all practical purposes, the voltage drop can be considered constant at one volt per contact. This loss, therefore, varies directly with the load current. The brush friction loss depends upon the number and size of brushes, the material of the brush and the condition of the contact surfaces, the brush pressure and the peripheral speed. The brush area for a given current rating is limited and cannot be reduced below an accepted value so that the total brush loss for a given set of conditions cannot be reduced except by decreasing the commutator diameter. Roughly, as the diameter is reduced the brush width must also be reduced, so that to maintain the required brush area more brushes must be added. This requires a longer commutator with resulting larger spans between supporting rings or greater overhang, both of which result in greater stresses and deflections with an increase in bar-to-bar roughness for a given temperature rise. Obviously then, it is not desirable to specify too low an operating temperature for the commutator as this will require a greater heat dissipating area, with resulting greater stresses, deflections, and roughness, with accompanying poorer commutation.

What then limits the temperature of a commutator in an upward direction? Not limitations of temperature of the mica between commutator bars and between the bars and the ground parts, that is, the vee-ring or shrink-ring mica, as this mica will withstand temperatures considerably higher than permissible or acceptable for successful commutator operation. Extremely high-temperature operation of the commutator could result in damage to the insulation on the armature coils due to heat flow from the commutator up through the necks and into the armature coil. However, the thing that limits commutator temperature is the ability of the commutator to go through a temperature cycle without bar-to-bar roughness and this depends primarily on the characteristics of the insulating mica used in the commutator and the processes used in building the commutator.

At the present time, full-load continuous-operation acceptable temperatures for commutators of class *A* insulated machines are 105 degrees centigrade and of class *B* insulated machines 125 degrees centigrade, with temperatures measured by thermometers, and with no allowance for hot spots, as obviously the maximum temperatures can be measured directly. Based upon present experience and designs, higher temperatures than 125 degrees centigrade for continuous operation are permissible, probably in the neighborhood of 150 degrees centigrade, still permitting successful operating commutators.

2. Influence of Heat on Materials Other Than Insulation

There is another limitation on the operating temperature of commutators due to the nature of the material used. Commutator copper itself must not be heated to too high a temperature or it will become annealed and thus lose its mechanical strength. The annealing temperature is not definite for copper but is influenced by time. For instance, commutators can operate indefinitely at a temperature of 150 degrees centigrade without any chance of annealing the copper. If the temperature is raised to 175 degrees centigrade, copper will not anneal immediately as it takes hours and days to anneal the copper thoroughly. If the temperature is increased appreciably above 200 degrees centigrade, the copper can be damaged in a short space of time.

Another limit in commutator temperature operation is the solder used in attaching the armature coils to the commutator necks. Ordinary solder melts at 180 degrees centigrade. Hard or tin solder melts at 220 degrees centigrade. These solders if used in commutator bar construction can be used without permanent damage to the commutator copper when soldering. However, if the commutator is subjected, for short durations of time, to very high temperatures, the solder may melt and be thrown out due to centrifugal force. This then forms high resistance joints or open circuits in the armature winding and sparking results.

Commutators for high-temperature-operating machines, such as railway motors, are usually made of silver-bearing lake copper as this material has better temperature creep characteristics and will better stand the stresses due to higher-temperature operation. The use of higher-temperature solders, melting at temperatures between 250 and 300 degrees centigrade, will eliminate the problems of the joints between the commutator necks and armature coils opening up due to high temperatures of operation and stresses of rotation. Its use, however, introduces problems of soldering without annealing the copper bars during the soldering operation, especially on those commutators having solid necks. Brazed or phosphorous solder joints which will stand relatively high temperatures could be used, but such joints do not permit satisfactory opening for removal of armature coils in case of repairs or replacements and there is the possibility of damage to the coil insulation in its use.

Brushes of carbon, carbon graphite, and copper graphite types are baked at temperatures far above those experienced in service. However, these brushes have shunts of stranded flexible cable attached to them by riveting or soldering and operation at too high a temperature will result in selective action and unequal current distribution, with resulting overloading of some brushes. This will cause overheating of the brush shunts, giving discoloration and brittleness to these shunts as well as the melting of the solder used in the shunt attachments, causing still further detrimental operation. Too high an increase in temperature operation of current collecting parts always results in poorer operation, more rapid brush wear, and higher maintenance costs.

Higher temperatures will adversely affect the insulating treatments used on

the punchings. In some cases varnish treatments will have to be supplanted by other forms of insulation. It can also detrimentally affect varnish treatments applied to various types of insulating pieces.

Oil-lubricated sleeve bearings may be affected by machine temperature and in extreme cases with high operating temperatures, external cooling of the bearings must be used. In the past oil cooling of the bearings by circulating water through pipes embedded in the bearing shell was used. Today the tendency is to use external coolers and circulate the oil through these coolers.

3. Problems of Expansion and Contraction Due to Temperatures

Method of bearing support as well as bearings themselves are affected by the temperature of operation. Antifriction bearings must not bind, neither must they have too loose a fit or they will be noisy and eventually give trouble in operation due to this looseness. However, if the machine operates at relatively high temperatures, the antifriction bearings must be of the loose-fit type having greater than normal clearance between the balls and races when at room temperature so that while there may be some extra looseness when the bearing is cold, normal tolerances will be secured at operating temperatures. Antifriction-bearing machines must have at least one bearing free to move endwise with temperature expansion. This means that where provision must be made for end thrust, end thrust in both directions must be taken by the bearings on one end of the machine only.

Most difficulties on induction motors due to temperatures are in connection with squirrel-cage windings. On those motors having wound rotors the problems are similar to those of d-c machines, commutators of course excepted.

On the former types of windings, the bars in the rotor slots are usually of copper and project beyond the ends of the punchings, where they are attached to the end rings. The end rings are made of copper, brass, or bronze. In the usual construction, the bars are brazed to the end rings. The difficulties encountered are due to the temperature expansion of the end rings. As they get hot, they expand in diameter and in so doing, bend the ends of the bars outward. On cooling, the reverse bending occurs. Repeated cycles of heating and cooling, due to repeated starting and stopping and changes of load, can cause these bars to break. The breaks occur in the bars between the laminations and the end rings. A break of a brazed joint is a rarity.

It can be shown that the loss produced in the squirrel-cage winding during starting is equal to the kinetic energy stored in the rotor and its connected load at rated speed. Since the starting periods are of short duration, 10 to 15 seconds on large machines, most of this loss is absorbed in the squirrel-cage winding, since this short time does not permit dissipation of the loss in the surrounding air. On slow-speed motors the WR^2 of the rotor itself is quite high and the WR^2 of the load may be several times that of the rotor, in many applications such as induced draft fans, grinders, choppers, and saws. In all these instances the large amount of loss raises the squirrel-cage-winding temperature to a high value with corresponding untoward results. By using brass or bronze end rings of higher resistance, larger cross-section rings can be used with no change in total resistance but with increased heat absorbing capacity. This results in less temperature rise, less expansion, and less breakage of bars.

On the smaller sizes of induction motors, where very small air gaps are used, very high temperatures will result in the rotor scraping on the stator at times. The rotor will run hotter than the stator so that the expansion will be greater, especially on high-slip motors which have many applications to take advantage of the flywheel effect that the high slip permits. Since production dictates noncircular outside-punching peripheries to get the maximum number of punchings from a given sheet of steel, resulting in only a portion of the punching periphery being held in the stator frame, the expansion of the stator punchings will not be symmetrical. This results in unequal expansion of the inside diameter of the stator punchings so that with the expansion of the rotor, the air gap will be so small at some point around the periphery of the motor that the rotor will rub on the stator. Even where the expansion does not actually cause the rotor to rub the stator, the air gap at some one point will be so small that the unbalanced magnetic pull will deflect the shaft enough to cause actual rubbing of the rotor on the stator punchings. Higher temperature rises will also require larger press fits of the punchings on the shaft so that the increased unequal heating of the punchings and the shaft will not cause the punchings to become loose on the shaft.

If higher-temperature-rise motors were used, especially in the larger sizes, the motor dimensions would be decreased, resulting in still higher temperature rises of the squirrel-cage winding with again unfavorable characteristics.

Collectors as used on the a-c end of synchronous converters, wound-rotor induction motors, and rotating-armature a-c machines are also subjected to temperature limits. These limits, since there are no bar-to-bar roughness conditions to be met, can be somewhat higher than for commutators. A safe ultimate temperature of 150 degrees centigrade could be used for collector-ring operation. The connections to collector rings are usually made by means of rods threaded into the collector material below the body of the ring surface. These threaded rings are usually sweated into position and too high a temperature operation of the collector rings, even for short periods of time, will result in the melting of this solder. High temperatures on collector rings have a tendency for the rings to become out of round, particularly on the large sizes, resulting in a roughened surface and accompanying poor operation and faster brush wear. On the larger size collector rings used on synchronous converters the spokes or arms can be made S shaped instead of radial so that the stresses due to expansion will not tend to distort the ring from a true circle. The ring body can also be made of relatively heavy cross section, even T shaped, in order to hold the ring surface as concentric as possible with an increase in temperature.

On relatively long-core d-c machines the ends of the field coils are not supported other than by the material itself and being free to move due to expansion, no chafing of the insulation results.

In the largest sizes of turbogenerators, with lengths of 20 to 25 feet between bearings, temperature rises up to 85 degrees will give elongations of approximately $^1/_8$ inch to $^9/_{16}$ inch in the various parts. The steel parts of these long-core machines operate at lower temperatures than the copper conductors, and since copper has a greater temperature coefficient of expansion than steel, there can be a total difference of endwise expansion of approximately $^3/_{16}$ inch of the copper conductors over that of the steel rotor, in which the copper conductors are embedded. Overload requires increased excitation and gives a greater increase in copper losses than increase in the iron loss, thus further accentuating this difference of expansion.

On these high-speed turbogenerators, the centrifugal force, due to the weight of the conductors in the rotors, exerts such enormous forces against the underside of the slot wedges that the conductors are

partially restrained from total movement in respect to the iron, throughout part of the total length due to those different temperatures and coefficient differences. Thus, most of the relative movement takes place at the ends of the rotors. This has in the past resulted in the insulation and bracing in the end rings of the rotors being chafed and can result in ultimate failure. However, improvements in insulation and the design of the end ring bracing in present designs give a construction that operates satisfactorily. A further increase in temperature rises would again extend the expansion beyond the limits of satisfactory operation.

On the stators, with vent ducts spaced in the iron for adequate ventilation, the insulated conductors will be exposed in the vent ducts. The insulation, being unrestrained by any slot sides in the vent ducts, will bulge with time, into these vent ducts. Since, as in the rotors, the copper conductors expand more than the core iron, a relative movement of the former will cause chafing of the coil insulation at the vent ducts. A large number of machines having a 60-degree-centigrade rise of insulated coils have operated for 15 years without trouble due to this elongation. An attempt, however, to increase this temperature rise from 60 degrees centigrade to 100 degrees centigrade on comparable size machines gave only a few years life due to failure of insulation at the vent ducts due to the endwise expansion differential. Failures of this nature are due to the pulverizing of the mica flakes due to the repeated cycles of chafing caused by heating and cooling with load changes.

Thus, it can be seen that excluding temperature limitations of the insulation on windings there are many features of machines, both electrical and mechanical, that place temperature limits on the operation of rotating electrical machinery. There are still other problems in connection with temperatures that vitally affect the design and operation of the machines.

From the performance standpoint, an increase in temperature rises, permitting more output from a given size and weight of material, reduces the margin, particularly of overload characteristics, even on short-time overload ratings. For instance, applying a higher-temperature-class insulation to a given design d-c machine with a redesign in the loading ratios of flux capacity to current capacity, in order to obtain a balanced design for the higher permissible temperature rises, will not permit increased overload commutating capacity in proportion to the increased capacity secured at the expense of increased temperature rise. Except for working the iron harder—that is, increasing the flux densities, giving a relatively lower armature-current loading—the overload commutating capacity is unchanged. In fact, the higher temperature operation of the commutator at the increased full-load rating, resulting in a somewhat higher bar-to-bar roughness, decreases slightly the commutating ability at any given short-time overload rating. Commutating overload ability is usually limited by the flux-carrying capacity of the commutating pole, which obviously is not increased by higher permissible temperature limits. Thus when higher ratings at higher temperatures are specified and secured, overload ratings must be decreased. However, on those applications where heavy overloads are not required or are of infrequent occurrence, and not of very great magnitude, higher-temperature machines of smaller size and weights can be produced.

Inherent voltage regulations, especially of d-c machines, drop off quite rapidly above normal full-load ratings. Increasing the ratings with accompanying greater temperature rises is secured at the expense of poorer voltage-regulation performance.

Many times extraordinarily good performance in the line of efficiencies is required from machines by the purchasers, while at the same time high temperature rises are permitted. Obviously if materials are worked very hard to get minimum material for maximum output, with resulting high temperature rise, efficiency must be sacrificed. Extremely high efficiencies can only be secured by not working all materials up to the maximum and some class *B* rated machines may have temperature rises falling in class *A* ratings simply because sufficient material had to be used to secure high efficiencies, resulting in minimum losses and relatively low temperature rises.

Machines may sometimes be purchased by customers specifying class *B* insulation, where the actual requirements could be met with class *A* insulation features. This is done intentionally so that for emergency operation the equipment can operate at higher temperatures without failure. In this connection, distinction should be made between the temperatures encountered in frequent short periods of cycles of operation and those encountered in continuous operation. Obviously high temperatures are considerably more detrimental for continuous operation.

Railway motors and other propulsion equipment require maximum output in minimum space and with minimum weight. This equipment, therefore, logically belongs in high-temperature classification and some sacrifice of operating life, increased maintenance, and limitations on some performance characteristics are permissible to get maximum output rating with minimum space and weight.

It is not the purpose of this paper to discourage the use of higher temperatures in rotating electrical machinery as in many cases such a step is very desirable, but it is the purpose to indicate the many factors that are vitally affected by such increase in temperatures. The use of higher temperatures will bring new problems along many lines, especially in large size machines. Caution in procedure, based upon experience gained, is advisable. Evolution rather than revolution of existing standards upward should be the trend.

Discussion

Felix Konn (General Electric Company, Erie, Pa.): I would like to emphasize Mr. Lynn's very appropriate statements about the higher operating temperature of traction motors and about the temperature of commutators.

If we assume that, by increasing the current and the speed, we obtain more output from a given piece of commutating machinery (by accepting higher temperature rises) this will result not only in higher commutator temperatures because of the increased losses but also in an increase in the commutating duty.

If we think of the commutating duty in terms of the reactance voltage, determined as the product of:

$$\text{commutated current} \times \text{rpm} \times K$$

(where K is determined by the design of the machine) we see that whether we increase the current or the speed or both, we increase the commutating duty. This will result in increased commutation loss, causing an additional temperature rise of the commutator and of the armature winding, but, more important still, if the commutating capacity of the machine is inadequate for the increased load, this higher commutating duty will endanger the performance of the machine by causing excessive sparking at the brushes resulting in burning of commutator segments and rapid brush wear.

It is, therefore, very important that, in the design and manufacture of light-weight commutating machinery operating at high temperature rises, considerable attention be given toward providing the most favorable commutating conditions (electrical and mechanical) in order to maintain the proper balance between commutating and heating capacity. This consideration has governed the design of d-c and a-c traction motors and, far from hindering the progress toward

higher outputs per pound, the fact that each machine has, so to speak, two ratings which should be matched one to the other has resulted in continued advances in both directions of heating and commutating capacity.

E. F. Dissmeyer (The Commonwealth and Southern Corporation, Jackson, Mich.): Mr. Lynn's discussion of "Effects of Temperature on Mechanical Performance of Rotating Electrical Machinery" presents a number of important items which should be given serious consideration when contemplating revision of our present standards. Mr. Lynn's paper covers in detail certain of the comments which the writer outlined in his discussion of Mr. Hellmund's paper "Rating of Electric Machinery and Apparatus" (AIEE TRANSACTIONS, volume 58, 1939, pages 499–503).

A number of failures of synchronous-condenser and frequency-changer rotors have occurred due to mechanical damage resulting from thermal effects. Expansion or movement of conductors has resulted in turn-to-turn and other types of rotor-insulation failures. Inspection of rotors has also disclosed many other troubles resulting from thermal effects, such as distortion or creep of amortisseur windings. The design of such rotors should not present any particularly difficult mechanical problems and consequently many of the troubles which we have with large machine rotors can be directly attributed to the fact that we permit rotors to operate at relatively high temperatures. There consequently appears to be considerable justification for reducing the permissible temperature rise of large machine rotors.

F. W. Gay (Public Service Electric and Gas Company, Newark, N. J.): The mechanical limitation imposed on a machine due to the fact that the lineal expansion of steel is only two-thirds of the lineal expansion of copper becomes most acute in very long 3,600-rpm turbine generators.

As an instance of this limitation it was at first expected that a 50,000-kw 3,600-rpm synchronous generator rated on the basis of 87-degrees Fahrenheit cooling water could carry 55,000 kw in the winter with a cooling water temperature of 50 degrees. With this idea in mind, a large refrigerating manufacturer was asked to submit a proposition to refrigerate the summer cooling water of 87 degrees Fahrenheit to 45 degrees Fahrenheit, well below the average winter temperature. The figure submitted to cover the cost of refrigerating machinery to give the expected 5,000 kw of incremental capacity with a power consumption for this machinery of approximately 125 hp was approximately $15,000. This looked like an attractive proposition, but the generator manufacturer quickly explained that even if the cooling water were cooled close to zero degrees centigrade no incremental kilowatts could be obtained. Apparently the limitation on this machine was the unequal mechanical expansion of its component parts rather than any hot-spot temperature.

It would appear that the time has come when copper conductors must be directly refrigerated and maintained at a temperature two-thirds that of the surrounding iron. When this can be achieved the expansion of the copper will equal that of the steel and the mechanical bugbear outlined in Mr. Lynn's paper can no longer frighten us. New refrigerating materials now available may soon make this practicable.

C. Lynn: Mr. Dissmeyer's and particularly Mr. Gay's experiences in higher-temperature operations of rotating electrical machinery stress the difficulties on insulated conductors due to expansions encountered in such operations. Obviously, these difficulties can be minimized and the limits extended somewhat by proper design. Too high-temperature operation will be at the expense of shorter life of the machine.

The point of balanced design between commutation and heating capacity in commutating machinery, as brought out by Mr. Konn, is well taken as the one of these which first reaches its limit determines the capacity of the unit. In this same connection it should be noted that a requirement of too low a temperature operation can lower the output capacity of a machine. For instance, for a given amount of loss on a commutator, the temperature rise can only be lowered by increasing the heat dissipating surface. If this is accomplished by increasing the length of the commutator bars, additional rotational stresses will be set up in them due to the greater spans between vee-ring supports. This gives a poorer mechanical operating commutator and can give inferior commutation even at reduced temperature rises.

The Rating and Application of Motors for Refrigeration and Air Conditioning

PAUL H. RUTHERFORD
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Synopsis: This paper describes the procedure and practical results to date in applying single-phase motors to refrigeration compressors. The applications are primarily torque applications, temperature considerations being of secondary importance.

A line of high-torque motors has been developed to meet the high starting and accelerating torques demanded by the compressors. Utilization of these torques results in running loads considerably higher than rated name-plate loads, without exceeding safe operating temperatures for the insulation life requirement.

To meet these requirements a revised method of rating refrigeration motors on a starting and accelerating torque per horsepower and a starting efficiency basis is described. This method more clearly specifies a motor so that a more satisfactory application would be obtainable both from the standpoint of the user and the public utility company or code authority.

THE continued growth of mechanical refrigeration in the past 15 years has greatly increased the number of single-phase electric motors used. There are more motors in the range of one-third horsepower to three horsepower being manufactured and applied to refrigeration compressors than for any other use. Practically all of these are connected to the lines of the public utility systems, and their installation is subject to the rules of the National Electric Code, Underwriters Laboratories, etc., besides the rules of the public utilities. From the standpoint of the user, the initial and operating costs are important as well as dependability and quietness of operation. Since the horsepower rating and temperature rise as stamped on the name plate have grown to be a poor description of the motor, it is thought advisable to consider better ways of rating motors as applied to refrigeration compressors. Inasmuch as the starting and accelerating torques rather than the temperature rise at name-plate horsepower are the determining factors in the selection of a motor, it may be necessary to include these in the future standards. The purpose of this paper is to show how particular motor characteristics have come to be used and to suggest a possible means of rating this group of motors for the future.

Paper number 39-18, recommended by the AIEE committee on electrical machinery, and presented at the AIEE winter convention, New York, N. Y., January 23–27, 1939. Manuscript submitted November 30, 1938; made available for preprinting December 9, 1938.

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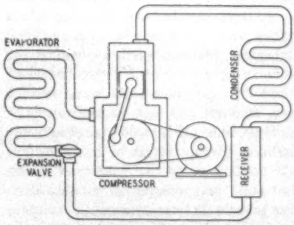


Figure 1. Diagrammatic sketch of refrigeration system

Selection of Motors

All mechanical refrigeration today is performed by vapor-compression machines. Figure 1 shows diagrammatically such a system. The liquid or refrigerant (usually Freon, methyl chloride, or sulfur dioxide) is alternately liquefied and vaporized. Refrigeration is produced by the latent heat of vaporization of the refrigerant. The vapor resulting from this vaporization in the evaporator or cooling element is drawn into the suction or low-pressure side of the compressor. The compressor then converts this low-pressure gas into high-pressure gas and forces it into the condenser. Here it is liquefied through cooling by means of water or air. The liquid refrigerant is then allowed to return to the evaporator through an expansion valve or restricted orifice.

The function of the electric motor in this system is to drive the compressor which compresses the low-pressure gas into high-pressure gas. The pressure in the crank case or at the low-pressure side of the piston is referred to as "back pressure" and the pressure on the high-pressure side or condensing side as the "condensing" or "head pressure." In a given system, the condensing and back pressures and the speed at which the compressor is driven are the determining factors in the amount of starting and accelerating torque required of this motor, as well as the operating load.

The motors used on these systems are the single-phase repulsion-start induction-run type in sizes of one-fourth horsepower, to three horsepower. Capacitor motors are beginning to be used in the one-fourth-horsepower, one-third-horsepower, and one-half-horsepower sizes but seldom little above these ratings because of the high starting currents compared with the other type motor. Practically all the refrigeration systems now using these sizes of motors are expansion-valve systems and the "pull down" is so short that it can be said to be no more severe on the motor from a temperature standpoint than the regular loads during cycling. By "pull down" is meant the first running period after installation or extended shutdown.

The application of the motor to the refrigerating unit is usually in the hands of the refrigeration engineer or a field installation engineer. Because of their desire to keep down the initial cost (as the cost of the motor is usually a large part of the cost of the condensing unit), the refrigeration engineer naturally will use all the available torque and carrying capacity of the motor at hand. In a refrigeration unit we shall show that the limiting load is not the running load, but starting and accelerating under the most adverse conditions. This is another way of saying that the motors are selected on a starting and accelerating torque basis rather than on a temperature rise at name-plate horsepower basis.

Suppose, for example, a new unit is to be manufactured. A compressor having a suitable bore and stroke based on previous experience of cost, etc., is designed and built. The condenser is selected in the same manner. The evaporator or cooling unit is designed to meet the demands of the load. This gives the engineer a unit on which to base his tests. As the majority of compressors are belt-driven, the speed is regulated by pulley sizes on the motor.

In any given unit the condensing pressure is a function of the effectiveness of the condenser. This pressure varies in the same manner as the pressure-tempera-

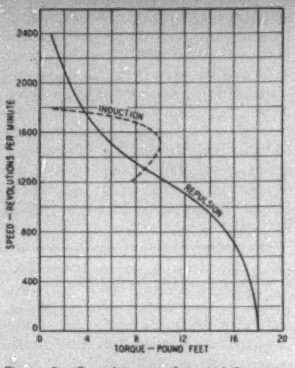


Figure 2. Speed-torque characteristics curve of one-horsepower repulsion-start induction-run motor

ture curve for saturated vapor for the refrigerant used. For various cooling-water and air temperatures that are likely to be encountered, and by a few tests on the effectiveness of the condenser, the range of condensing pressures can be determined. Further, by knowing the type of load on the system and the temperature of the evaporator a range of back pressures can be determined. With this range of condensing and back pressures defined the unit can be tested for motor requirements. A pulley is selected giving an average speed and tests are started.

For starting or breakaway in a given compressor the greatest torque required of the motor is at the condition of greatest difference between the condensing and back pressures. This condition occurs on certain types of loads and usually when the back pressure is very low. A pulley is then selected that will start the compressor under this worst condition at some arbitrary voltage limit from 10 per cent to 20 per cent under the name-plate rating.

This worst condition of condensing and back pressure usually occurs sometime during the running cycle and not after the unit has been off and is ready to start. If there is a momentary power failure and power returns there must be sufficient torque available to start the compressor.

The accelerating of the compressor requires a torque which is nearly proportional to the absolute back pressure. The pull-in or minimum accelerating torque is then the limiting factor in the amount of load the motor will accelerate. The high accelerating torque is necessary because of the work which is being done during each stroke of the piston. This work is the compression of the gas and it will be seen that with greater back pressure more gas is compressed during each stroke of the piston. Usually, it is found that the pull-in or accelerating torque of the motor is the limiting factor and not the starting torque. This is more noticeable on repulsion-start induction-run motors because of the high ratio of starting to pull-in torques.

Since the back pressure at which the unit runs is determined by the nature of the load, the range of back pressures will be great. If the evaporator or cooling coil is to cool an ice-cream cabinet the temperature of the coil will be relatively low, around ten degrees Fahrenheit. If the cooling coil is to be used for air conditioning, its temperature will be much higher, probably 40 degrees Fahrenheit. The back pressure in the former case is low and in the latter case high (assuming a given refrigerant). Since the accelerating torque is a function of this back pressure, there should be a theoretical best speed of the compressor for each back pressure. Since this is not practical the same compressor is usually provided with three different pulleys which are used for low, medium, and high back pressures.

Thus the refrigeration engineer has utilized all the torque of the motor in the application to the compressor. The last point he checks is the running load. For present-day compressors the running load when the torque is completely utilized is usually beyond the name-plate horsepower rating. Although a large number of cases require intermittent operation of the motor, the design of the whole unit from a temperature standpoint must allow for continuous operation of the motor.

For example, take a typical unit driven by a one-horsepower 110–220-volt 1,750-rpm 60-cycle single-phase repulsion-start induction-run motor. The speed-torque characteristic curve is shown in figure 2 and the running characteristics are shown in figure 3. The compressor was tested as in the procedure above and it was found that three pulleys for low, medium, and high back pressures were satisfactory, giving compressor speeds of 635, 570, and 510 rpm. The characteristics of the compressor are partly shown on figures, 4*a*, 4*b*, and 4*c*. Freon (*F*-12) is used as a refrigerant and a water-cooled condenser is shown. Similar data are available for the same compressor with an air-cooled condenser.

A typical application of the condensing unit would be made in a manner as described above. For selected values of 50-degrees-Fahrenheit refrigerant temperature and 70-degrees-Fahrenheit condensing water, the data given in table I appear.

The motor on the installation was found to accelerate the load at 90 volts on a 110-volt system. Satisfactory starting

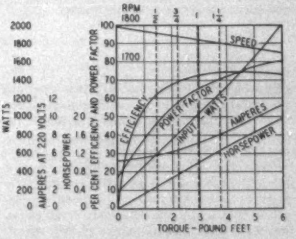


Figure 3. Running characteristics of one-horsepower repulsion-start induction-run motor

conditions were also assured. The temperature rise of the motor as measured by resistance at this load was 46 degrees centigrade in the rotor windings and 38 degrees centigrade in the stator windings. Thermocouple measurements for the same load gave 44.6 degrees centigrade and 40.4 degrees centigrade.

If, however, the load is increased because of an increase in the condensing water temperature from 70 degrees Fahrenheit to say 80 degrees Fahrenheit, the horsepower required rises to 1.57. At this new shaft load the temperature rise by resistance is 46 degrees in the stator windings and 54.5 in the rotor windings. At an increase in line voltage from 110 to 120 volts (which is very common in service today) the temperature rise at 1.57 horsepower load will be 58 degrees centi-

Table I

Condensing Water (Deg F)	Btu per Hour Compressor Output	Back Pressure (Pounds per Square Inch)	Motor Input (Watts)	Motor Shaft Output (Horsepower)	Temperature Rise by Resistance (Deg C)		Temperature Rise by Thermocouple (Hot Spot) (Deg C)
70	23,500	46.7	1,395	1.40	46	(rotor)	46.6
					38	(stator)	40.4
80	22,600	46.7	1,530	1.57	54.5	(rotor)	53.3
					46	(stator)	48.9

grade by resistance and 60 degrees centigrade by thermocouple in the rotor windings. (All the thermocouple values are the hot-spot values obtained from a large number of locations.)

The temperature rise of 58 degrees centigrade continuous at the 1.57-horsepower load does not seem excessive because the load is a maximum. The load on the system cannot be changed unless the temperature of the condensing water rises. This is an ideal application of the motor however, as the user is getting the most refrigeration per dollar from the installed apparatus because he is using all the torque available in the motor and because the running point is at the point of maximum efficiency of the motor.

There are of course, a large number of other considerations in the selection of the motor for this refrigeration system. The starting current of the motor should be low enough to comply with the regulations of the public utility systems. The noise level of the whole system and particularly of the motor must be low as the installation is made where quietness is necessary. The magnetic noise of motors for refrigeration units has been given considerable attention. Although a design which gives low magnetic noise is essential, it has been found that improvements of manufacture to hold the air gap concentric have greatly assisted in producing a consistently quiet product. Due to the nearly universal use of V-belt drive it is necessary to build motors with end-play takeup or cushioned for end-bump. In general, the large production of refrigeration motors has helped the motor manufacturer to improve the quality and decrease the cost of motors in these sizes. The characteristics and ratings of motors used on refrigerating systems, because of the large quantity of motors used for this purpose, have greatly influenced the characteristics and ratings of other motors. It is therefore logical to discuss the ratings of motors as used on refrigeration systems.

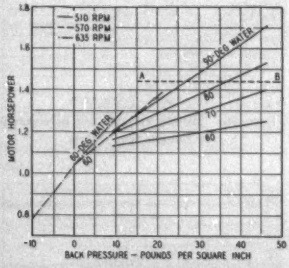


Figure 4a. Condensing-unit characteristics

A-B—Line of maximum loading

Motor Ratings

With the use of the torques and overloads described above, other problems are introduced. The horsepower marking along with the corresponding full-load current as placed on the name plate are used by various code authorities for selecting the proper wiring and fusing. The control engineer uses these currents in selecting the proper overload control. The public utility uses the horsepower rating as stamped on the name plate to set the maximum allowable starting current. Further, the whole electrical industry refers to the motor in terms of the marked horsepower. However, a newer use of the horsepower markings has arisen in the refrigeration industry and that is the naming of the refrigeration unit by the horsepower of the motor used on it. This latter practice transfers the variations of compressor applications, designs, and inequalities of the whole system to the motor when comparing various units.

Gradual development and improvement of design and manufacture of refrigeration motors without an increase in the physical dimensions has further raised the torque obtained from a given quantity of materials without increasing the name-plate rating. It is felt that here we have a typical case of a motor rating based on carrying capacity at full load as now shown by AIEE Standards, not coinciding with actual practice.

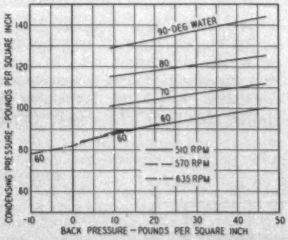


Figure 4b. Condensing-unit characteristics

When we suggest formulating a new method of rating for these motors, we immediately enter new territory.

It is felt that a service factor is a makeshift way of showing the overload of these motors. It is not all-inclusive in that it does not give a true picture of the higher starting and accelerating torques and does not allow for starting current. It is felt that too much education of the code authorities would be necessary to get the proper wiring and fusing to accommodate the increased load without the nameplate stamping being accordingly altered.

It is pointed out that for refrigeration applications the required life of the motor seldom is greater than 15 years. Usually, in this length of time the unit is replaced by more up-to-date equipment. The running time for the average unit on a refrigeration application is much less than full time and actually nearly half time. On an air-conditioning unit the running time during the year is one-fifth to one-fourth of the total time. There are also a great number of cases where the on cycle for a large part of the life of the unit is so short that the motor does not reach its ultimate temperature during each cycle. The low ambient temperatures usually encountered give a further factor of safety for motor temperatures. An ambient temperature above 90 degrees Fahrenheit is recognized by a suitable decrease in compressor ratings and motor loadings by the refrigeration unit manufacturers. Further, on air-cooled condensing units the use of the fan on the motor shaft extensions to pass air through the condenser, usually cools the motor in addition to the fan within the motor itself. Therefore, on an insulation-life basis we have an excess of useful life of the insulation for a hot-spot temperature of 105 degrees centigrade. A further important point to consider is that the difference between the hot-spot temperature as measured by thermocouple embedded in the windings on motors of these sizes and the temperature as measured by an adjacent thermometer is very little. This leads us to the suggestion that for refrigeration applications, motors be rated 50 degrees centigrade. As the published tables of the refrigeration manufacturers show the

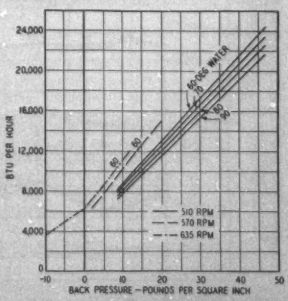


Figure 4c. Condensing-unit characteristics

permissible overloading, and as this overloading is not allowed beyond a point where there will be a temperature rise greater than 50 degrees centigrade, there would be no need for a service factor if the horsepower of the motor used has a 50-degree-centigrade rise as its name-plate stamping. If 40 degrees centigrade rise is used by the electric industry as standard, the refrigeration engineer will still load his motors to a 50-degree-centigrade rise and we will have loads out of line with name-plate ratings.

Specifying the temperature rating of motors used on refrigeration systems will not accurately define the motors as used today. This alone will not stop the practice of having a horsepower stamping on the name plate different from the actual horsepower load on the motor. However, since the motors applied and used on a torque and temperature basis and from experience over the past years torque values have been found which are satisfactory for refrigeration applications it is entirely possible to specify for motors on refrigeration applications the following:

(*a*). The accelerating torque per horsepower

(*b*). The starting torque per horsepower

(*c*). The starting efficiency in pound-feet per ampere locked-rotor current

The curves in figure 5 show the accelerating and starting torque per horsepower as found today. If, however, another curve of torque per useful horsepower is drawn, it will coincide closely with the torque per horsepower if the horsepower ratings were all moved up to the next higher horsepower ratings.

Figures 6*a* and 6*b* show the locked-rotor currents per horsepower for the repulsion-start induction-run and capacitor type motors. In figure 6*a* the currents are taken from present-day motors and based on the horsepower stamping on the name plate. Figure 6*b* shows the locked-rotor current per horsepower for the proposed name-plate stamping. For the repulsion-start induction-run motors the horsepower used was the useful horsepower as shown in figure 5 which is practically the same as the next higher horsepower rating. For the capacitor motor, the horsepower used was that obtained from present motors when rated 50 degrees centigrade rise. These starting currents per horsepower would be obtained if the present motors were designed for 50 degrees centigrade rise. Figure 6*c* shows the starting efficiency in torque per ampere locked rotor current. If then, 50 degrees centigrade rise is accepted the torques and starting efficiency could be selected as follows:

5.5 pound-feet per horsepower minimum accelerating torque

11.0 pound-feet per horsepower starting torque

0.5 pound-foot starting torque per locked ampere at 220 volts

As was pointed out previously, the starting torque available on the repulsion-start induction-run motor was usually much higher than necessary and the limiting torque of the motor on nearly all applications is the minimum accelerating torque. With the capacitor-start capacitor-run or capacitor-start induction-run motor this situation is not the same. Here the starting torque is less and the accelerating torque per horsepower is greater. See figure 7 for a speed torque curve of a capacitor motor. The starting torque per ampere or starting efficiency is much less. At the present time capacitor motors are not used in many places above three-fourth horsepower but from the data available the torques are as follows:

5.5 pound-feet per horsepower minimum accelerating torque

10.0 pound-feet per horsepower starting torque

0.3 pound-foot starting torque per locked ampere at 220 volts

It is therefore felt that here we have torque values which specify the motor and which can be tied up with the proposed name-plate rating. They are satisfactory from the standpoint of the user, the starting currents agree with those required by the public utilities, and the control engineer can select proper control within the limits of the National Electric

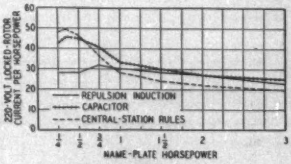


Figure 6a. Starting currents per horsepower for present-day motors

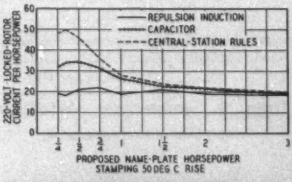


Figure 6b. Starting currents per horsepower for proposed 50-degree-centigrade motors

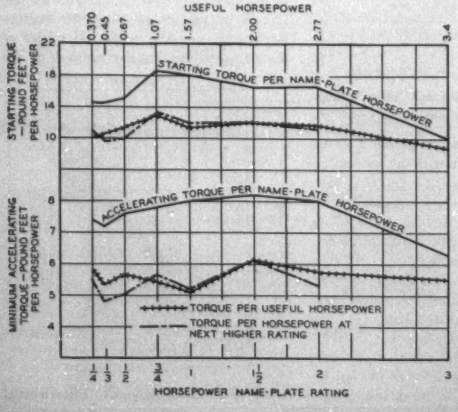

USEFUL HORSEPOWER
STARTING TORQUE—POUND FEET PER HORSEPOWER
STARTING TORQUE PER NAME-PLATE HORSEPOWER
ACCELERATING TORQUE PER NAME-PLATE HORSEPOWER
MINIMUM ACCELERATING TORQUE—POUND FEET PER HORSEPOWER
TORQUE PER USEFUL HORSEPOWER
TORQUE PER HORSEPOWER AT NEXT HIGHER RATING
HORSEPOWER NAME-PLATE RATING

Figure 5. Starting and accelerating torques for various horsepower ratings

Code. These also prevent the false marking of name plates.

It may be argued that specifying of the torques per horsepower will tend to limit new developments or improvements in the present motors. There is obviously nothing to prevent the engineer from increasing the starting or accelerating torque per horsepower if there is no increase in starting current. There is also nothing to prevent the engineer from increasing the horsepower carrying ability of a certain motor if he does not change the torque relations as set.

The increasing use of hermetically sealed compressor units makes the motor

ratings for these units a pertinent subject. The temperature rise of the motor here is dependent upon the refrigeration manufacturer. If, however, the horsepower ratings are not set on a similar basis of torques per horsepower the same bad practice of false name-plate stamping will creep into the ratings of these motors. It is not the purpose of this paper to state what these should be at the present time.

It will, of course, be argued by some that this basis of rating may be satisfactory for refrigeration applications, but not for others. From the standpoint of the

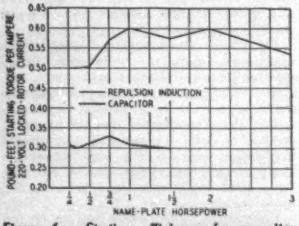


Figure 6c. Starting efficiency for capacitor and repulsion-start induction-run motors

public utility company the starting current per horsepower could not change and if less starting torque is necessary there would probably be a decrease in starting current.

It must always be kept in mind that standards or ratings set by the electrical industry should allow the large-scale user to get the fullest possible use of the motor for the requirements peculiar to its application. If the standards do not allow this, large users of motors will either break the standard or manufacture motors for their own use.

Conclusion

It has been shown that in the application of refrigeration motors, the accelerating torque and starting torque consistent with starting-current limitations with a 50-degree-centigrade temperature rise are the determining factors.

The recommendations for setting values of starting torque per horsepower, accelerating torque per horsepower, and starting efficiency in torque per ampere of locked-rotor current offer a logical and definite basis of rating for these motors. These tie together the present two types of high-torque single-phase motors so that the same horsepower rating on the name plate can be used on both for any given compressor application. These also offer

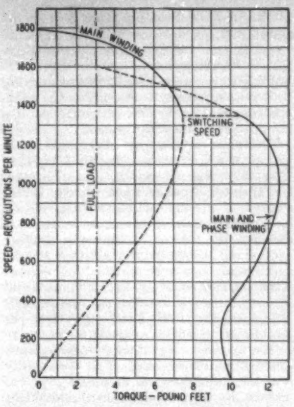


Figure 7. Speed torque characteristics curve for one-horsepower capacitor-start capacitor-run motor

a method of rating motors for use in hermetically sealed units which are increasing in use for all sizes of refrigerating units.

Discussion

D. F. Alexander (nonmember; General Motors Corporation, Dayton, Ohio): This timely paper outlines an application problem which should be of great interest to those who design or create standards for small single-phase motors. The refrigeration and air-conditioning industry has become a larger user of these motors, and has special requirements which the familiar general-purpose motor does not meet. Manufacturing competition has forced an economy of motor materials to suit the job at hand, and the resulting line of motors calls for a reconsideration of existing rating standards.

It has been apparent in this field for several years that motor name-plate markings and application codes are out of line with practice. This has handicapped the manufacturer, the salesman, the contractor and the purchaser, not to mention the power companies and the sponsors of the National Electric Code. Attempting to find a suitable compromise among the various codes and standards now in force, it appears that all these interested parties have cause for complaint.

The selection of proper controls, wiring overload protection, and fusing for these motors is often based on the name-plate horsepower and current, despite the fact that such markings today give no indication of the actual motor overloads. Wiring and fusing are often inadequate, or must be replaced by the contractor before code authority approval can be obtained. Summing up, we have today a varying-duty motor load often far in excess of the motor rating, with fictitious name-plate markings. A revision is in order, to bring the marking more nearly in line with the facts. As Mr. Rutherford points out, a revision of these motors to a 50-degree-centigrade rise basis, from the present 40-degree-centigrade basis, would go far to remove the present confusion in this respect. In addition, suitable wording might appear on the name plate to distinguish these motors from the general-purpose type.

The paper describes the steps necessary in selecting a motor for a refrigeration compressor. You will note that the torque requirements, in general, determine the motor design, and not the temperature-rise at name-plate horsepower. For that reason, it would be preferable that the motor name plates be rated in terms of torque and starting currents. This is not practical, since the horsepower rating is the common term for identification of the complete unit as well as for the motor. As the next best thing, then, let us specify torque and current limits for the 50-degree-centigrade-rise refrigeration motor, in the manner described in the paper. It has been suggested elsewhere that a new series of service factors for 40-degree-centigrade motors be used, rather than a straight 50-degree-centigrade rating. This may be satisfactory for the motor manufacturer, but for those who must select control equipment and wiring for which there are no service factors, the problem might become more complicated than at present. The use of such service factors for *polyphase* motors five horsepower and larger may be justified, but does not come within the scope of these comments.

The original basis for selecting 40 degrees centigrade rise for general-purpose motors did not allow for an application such as this one. A number of important factors permit a higher temperature rise, as listed in the paper. New information on the life of class *A* motor insulation, as reported in other papers at this convention, leads me to believe that a 60-degree-centigrade rise rating for refrigeration motors might not be excessive. However, we must not overlook the effect of high temperatures on motor-mounted capacitors, the excessive copper losses due to the cumulative effect of heating at prolonged overloads, or the danger to the lubricating system. Severe overloads in some motor designs will also result in poor speed regulation. Everything considered, and noting successful experience during the last few years at 50 degrees centigrade rise, it would seem that this value would be best.

With the spread of commercial refrigeration and of air-conditioning units, the next few years will see a large increase in the use of single-phase motors from one-third to three horsepower. In this connection, it would be profitable to note the progressive and realistic attitude toward motor ratings as expressed in Mr. Hellmund's paper (AIEE Transactions, volume 58, 1939, pages 499–503). It would be very helpful if any changes in rating could be made promptly.

L. C. Packer (Westinghouse Electric and Manufacturing Company, Springfield, Mass.): This is an excellent paper outlining the application of single-phase motors for refrigeration compressors and the au-

thor's recommendations for rating of motors for this type of application are of considerable interest.

In the application of single-phase motors to refrigerating compressors, there are, as the author states, many things to consider.

For instance most domestic refrigerators use the hermetically sealed type compressors, using split-phase-type induction motors, whereas the commercial-type refrigerator units use both belt-driven and hermetically sealed type compressors.

The belt-driven type used in most cases uses the repulsion-type motor. The hermetically sealed type, as a rule, uses a capacitor start and run motor from approximately $\frac{1}{4}$ horsepower to $1\frac{1}{2}$ or 2 horsepower. Small air-conditioning compressors of the hermetically sealed type use capacitor motors of a little higher rating.

As the author states in his paper, it is essential that the motor have sufficient accelerating torque so that it will not pull out at the maximum back pressure and discharge pressure at the lowest expected voltage.

The starting torque required depends a great deal upon the type of compressor. The starting torque of a repulsion motor is greater than split-phase or capacitor-type motor; therefore it is adaptable in most cases for belt-driven-type compressors. It is well to have reserve starting and accelerating torque in this case to take care of cases where the belt may be tightened too much.

In the hermetically sealed compressor, which is gaining prominence rapidly, the starting torque required, at the lowest expected voltage, depends upon whether or not it is desired to use an unloader to equalize the pressures, before restarting after stalling. It is the designer's duty to get the best starting conditions at the lowest cost of the equipment and at the lowest possible starting current. Also keep in mind that he wants the highest possible efficiency with the necessary accelerating torque.

Assuming that no unloader is used. The motor of capacitor type must have sufficient capacity in the auxiliary-winding circuit to get the starting torque required. However, sufficient torque may not be obtained in some cases without impairing the performance under running conditions because the maximum starting torque is obtained when the reactance of the starting capacitor is equal to the reactance of the auxiliary circuit. The current in the auxiliary winding and the capacitor is also the maximum under this condition. If this condition does not give sufficient starting torque it does not pay to increase the capacity beyond the point where the reactance of the capacitor is less than the auxiliary winding reactance, as the starting torque starts to decrease because of the decreasing current in this phase and smaller phase angle between the main and auxiliary windings. The designer will then most likely put in an unloader to equalize the pressures. The starting torque required in this case is much less than without an unloader and the motor will require less capacity; in most cases at a saving and at a slightly lower starting current. It is even possible in many cases to use a single capacitor for both running and starting, thus effecting a further saving.

In the case just cited, the minimum cost is obtained which is important to the customer and the starting current satisfies the requirements of the power companies. Therefore, there is nothing to be gained by holding to a standardized ratio of starting torque to horsepower. As long as the starting torque is sufficient, it would be less costly to keep this ratio as small as possible.

The ratio of starting current per foot-pound starting torque would be higher than the proposed standard in this case, but as noted above no higher torque is necessary. While the capacitors in the circuit have some influence on the line current at starting, the current in the main winding at starting is definitely established by the accelerating torque required. This current is very nearly equal to the line current and in some cases greater than the line current. Therefore, the ratio of starting torque per ampere has very little meaning.

The author suggests a 50-degree-centigrade temperature rise. This apparently is a debatable question and may apply to motors for belted applications and might also come within the suggested values by Messrs. Alger and Johnson in their paper on "Rating of General-Purpose Induction Motors" (AIEE TRANSACTIONS, volume 58, 1939, pages 445–59). However, in hermetically sealed compressors, there are, as noted before, many conditions to meet. fifty degrees centigrade rise is too high with some types of permissible insulation and in some cases the higher temperature is too high for other reasons. There are some cases where the transmission of motor heat does not increase with load. There is then no definite relationship between temperature rise and horsepower. Thus, it appears that to set up a standard of rating motors for refrigeration and air-conditioning compressors without careful consideration of the problems of hermetically sealed units, may handicap the manufacturers of this class of apparatus with no advantages to the user. Of course, no one has to design the motor for a 50-degree-centigrade rise. But without some basis there is nothing definite from which to establish the horsepower rating.

Messrs. Alger and Johnson noted in their paper just mentioned that temperature rating standards do not apply to this class of motors. There is considerable merit to this thought, as well as to adhering to breakdown torque and starting-current rules, but the ultimate user may be paying in efficiency for a breakdown torque that is not required. Thus in the case of hermetically sealed compressors the application can be satisfactory with breakdown torque and starting torque below suggested values for a standard, resulting in economy in the size of the motor and yet with satisfactory starting current. Rotary-type compressors will require special studies concerning the application of motors to them.

Therefore, where hermetically sealed units are concerned, if the name plate is stamped with the horsepower and load current representing some standardized working load, and in line with the starting current rules, the desires of National Electric Code, Underwriters and power companies, and control engineers will be met. The name-plate current, however, may not tie up with the horsepower rating because auxiliary apparatus, fan motors for cooling, etc., will take some of the current.

R. A. Fuller (General Electric Company, Fort Wayne, Ind.): Experience with the application of motors to refrigeration and air-conditioning compressor drives indicates that the limiting factor will be one of the following:

1. Maximum continuous permissible load
2. Starting torque
3. Maximum, or pull-out torque
4. Accelerating torque

Repulsion-induction motors tend to be limited by accelerating torque or maximum continuous permissible load. The principal limiting factors for capacitor motors are starting torque and maximum continuous permissible load. Only in the one-sixth and one-fifth horsepower ratings has there been any indication that torques alone can be used for rating purposes.

Polyphase motors tend to be limited by maximum continuous permissible load, starting torque, or accelerating torque.

D-c motors tend to be limited only by maximum continuous permissible load.

It is therefore believed that the proposed method of rating has possibility of general application only in the fractional-horsepower single-phase ratings and further that its general application there is somewhat questionable.

Compressor designs enter into the torque requirements. For example, a four-cylinder compressor will tend to have a starting torque requirement approximately the same as a two-cylinder compressor of one-half the capacity. Thus, the construction of the compressor will have considerable influence in determining the limiting factor in the particular motor application.

The refrigeration engineer has considerable test data and empirical procedure on motor torque requirements and motor loading. Fundamentally, however, motors are still applied to these refrigerant condensing units by cut and try methods. The technical facilities of the present day should permit us to superimpose a motor speed-torque curve on a compressor speed-torque demand curve and thus accurately and readily determine the suitability of the motor. Work already done along these lines has shown some promise.

It is suggested that the torque elements of these applications might best be met by comparing speed-torque curves of the motors with speed-torque demand curves of the compressors. It is recommended that any rating method should include maximum continuous permissible load.

A. F. Lukens (General Electric Company, Lynn, Mass.): Mr. Rutherford has brought out the essential points of applying motors to refrigeration and air-conditioning compressors. The more important points are:

1. Motor size is determined by starting and pull-up torque rather than motor heating.
2. The pull-up torque is usually more important than starting torque.
3. Motor noise and end-bump.

He also states that capacitor motors have not had wide use in the sizes above three-fourths horsepower.

However, integral-horsepower capacitor motors can be designed that meet the re-

quirements pointed out by Mr. Rutherford of high pull-up torque, quietness, and end-bump and in addition have the advantage of high efficiency and power factor and high maximum running torque. The last is important as it prevents lowered efficiency and light flicker brought about by overloads, undervoltage, or inadequate flywheel, or the combination of the three.

Tests of integral-horsepower capacitor motors on compressors of different manufacture have proved that 300 per cent starting torque is ample, and that more than this is unnecessary. This checks Mr. Rutherford's twice repeated statement that for the repulsion-induction motor the pull-up torque and not the starting torque is the limiting factor. In other words, the repulsion-induction motor has an excess of starting torque.

Since pull-up torque and starting current are the limiting factors in starting ability, it is suggested that the third specification, namely, "the starting efficiency in pounds-feet per ampere locked-rotor current" be changed to the ratio of pull-up torque divided by locked-rotor amperes. This value is then a measure of the starting efficiency of the motor.

The pull-up torque of a well-designed capacitor motor should be greater than 200 per cent of full load torque on the present basis of rating and can be 220 per cent. The starting current of the capacitor motor is not more than ten per cent greater than the repulsion-induction motor as shown by figure 6. Using the most adverse values the ratio is 0.25 foot-pounds pull-up torque per locked-rotor ampere for both types of motors.

The application of motors to use the full extent of their torque ability obviously reduces the factor of safety of the motor under load, so that it is felt that protection of the motor should be supplied. An automatic reset overload relay actuated at least in part by line current provides excellent protection under all conditions of abuse without completely stopping the refrigeration. Such a device prevents damage to the motor under severe overloads without completely interrupting the refrigeration which in turn prevents wholesale spoiling of the refrigerated product. In the case of failure to start, the device removes the motor from the line for a time long enough for it to cool down before restarting. In the meantime, the head and back pressures have had a chance to equalize and the starting duty is easier. This "limping" operation of the compressor will eventually come to the attention of the user and can be fixed without total loss of refrigeration.

Chester Lichtenberg (General Electric Company, Fort Wayne, Ind.): Standards for electrical machinery and particularly electric motors may be grouped according to usage.

Dimension standards, including frame sizes, afford design convenience. They present a hazard since any design restriction hampers imagination and progress. Design standards may be developed by individual groups of engineers promptly responsive to new conditions, but do not appear to have a place in industry standards sponsored by trade associations such as National Electrical Manufacturers Association, Radio Manufacturers Association, and American Cotton Manufacturers Association.

Application standards are essential for the effective and economical usage of apparatus including electric motors. Application standards might include items such as maximum starting torque, maximum starting current, and rotor flywheel effect. These might well be included in trade association standards since they affect the manufacturer, the buyer, the user, and the public utility. Recommended practices or adopted standards for these and similar items would be genuinely helpful.

Rating standards, however, are broader in usage, more fundamental in concept, and should be more rigidly defined than either design or application standards. They should be so fundamental that they will accurately reflect wide varieties of designs and application. They should be so simple that ordinary folks can use them. They should be so definite that all users will understand them. They must be unbiased and therefore the result of joint deliberations. Hence rating standards for electrical machinery, as distinguished from design standards and application standards, are a unique standardizing function of the AIEE and the refrigeration industry as an example is watching, certain that the AIEE will do a good job of rating standardization.

B. M. Cain (General Electric Company, Lynn, Mass.): Every engineer recognizes that the approach to an application problem should be based largely on the requirements of the load without preconceived ideas as to the type of drive or its possible limitations. By such an approach the limitations of available types of drive can be clearly and carefully analyzed.

Mr. Rutherford has clearly demonstrated that for the refrigeration compressor there is a definite ratio between the accelerating torque and the torque at average load. He has also shown that the refrigeration engineer applies the motor largely on the basis of its ability to provide the accelerating torque required by the load. The only other essential requirement is that the motor must not fail due to overheating.

Tests have shown that the ratio of accelerating torque to useful running torque of a compressor is about 1.65. This means that, after allowing for ten per cent low voltage, the pull-up torque of the motor must be 1.65 divided by $(0.90)^2$ or 204 per cent.

An extra safety factor, advisable in accelerating torque to guard against a long accelerating period, brings this to about 220 per cent.

The breakaway torque of compressors is shown by test to be about 50 per cent greater than the torque at 80 per cent speed. Thus the starting torque of the motor must be 204 per cent $\times$ 1.5 or about 300 per cent. No safety factor is needed.

The torque requirements of any driving motor have thus been established at:

1. Pull-up torque—about 220 per cent of full-load torque.
2. Locked-rotor torque—about 300 per cent of full-load torque.

Any torque in excess of these values will not be useful and conversely any motor having less than these values cannot, in most cases, develop its useful capacity.

Examination of the speed-torque characteristics of various types of single-phase motors shows that for these starting and accelerating torques a limitation of starting current will always limit acceleration torque and not starting torque.

The minimum accelerating torque of well-designed capacitor motors or repulsion-induction motors is substantially the same. It can be conservatively as much as 0.25 pound-feet per ampere of locked-rotor current at 220 volts. This means that the locked rotor current of motors for driving compressors must be $1 \times 5{,}250/1{,}725 \times 2.20$ divided by $0.25 = 26.9$ amperes per horsepower.

That is, regardless of type, the starting current must be at least about 27 amperes per horsepower in order for the motor to carry its useful capacity.

By limiting the starting current to less than this amount the user is forced to sacrifice useful capacity which he has paid for on a horsepower basis.

On the other hand extending the starting current limit to higher values enables the manufacturer to pass on to the user economies in cost and performance obtainable with higher starting currents.

Recognition of this fact by some of the leading power companies has already started the trend toward higher allowable starting currents.

C. G. Veinott (Westinghouse Electric and Manufacturing Company, Lima, Ohio): Mr. Rutherford is to be complimented for presenting a useful and educational paper. He gives data on the application of motors to refrigeration and air-conditioning apparatus, thereby showing the underlying reasons for the specifications set up by this class of manufacturer.

His paper brings out into the open a fact long recognized by those familiar with this application of motors—namely that the horsepower rating stamped on the name plate does not adequately describe the capacity of the motor since the latter frequently carries from 30 per cent to 50 per cent overload continuously. The severity of this service is enhanced by the fact that the motors have to be able to carry these overloads in ambient temperatures appreciably above the established standard of 40 degrees centigrade. Thus, a one-half-horsepower motor used in refrigeration service is really a three-fourth-horsepower motor.

The author proposes to increase the horsepower stamping on the name plate to a value more nearly commensurate with the useful horsepower that the motor will develop, at the same time increasing the rated temperature rise from 40 degrees centigrade to 50 degrees centigrade. Without a doubt this honest straightforward proposal has unquestioned merits. By also increasing the ampere stamping to correspond with the new horsepower rating, much confusion among the control people and code authorities who specify the wiring, will be eliminated. Such a method of rating is more in accord with the objectives of an ideal rating structure outlined by Mr. Hellmund ("The Rating of Electrical Machinery and Apparatus," AIEE Trans-

ACTIONS, volume 58, 1939, pages 499–503). Unfortunately, however, this proposal may be opposed by the refrigeration manufacturers, particularly since some of them name their unit after the horsepower rating of the motor. Moreover, some of them seem to feel that, for a given unit of any size, the smaller the horsepower rating on the motor name plate, the more efficient the unit from a thermodynamic standpoint.

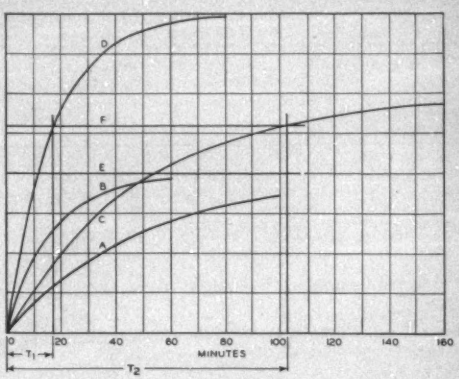
Also, if Mr. Rutherford's proposal were accepted, the motor manufacturers would have to be particularly vigilant to see that the refrigeration manufacturers didn't revert to their previous habit of applying overloads of 30 per cent to 50 per cent.

The author brings out the importance of adequate torques. He suggests certain torque specifications which are conservative and in accordance with present commercial motors. Why he specifies torques in terms of "pound-foot per horsepower" is rather puzzling. The present accepted method of specifying torques is in per cent of full-load torque. When specified in per cent, the figure becomes independent of the units used for measuring torque ("ounce-feet" is commonly used for fractional-horsepower motors and "pound-feet" for integral-horsepower motors) and is more nearly the same figure for motors of odd frequencies or different numbers of poles. Does Mr. Rutherford claim some unusual advantage for his new method of specifying torques?

Discussing the importance of locked-rotor amperes, the author proposes to specify them in terms of starting torque. If locked-rotor amperes are to be specified in terms of torque, we believe, concurring with Mr. Lukens, that they should be specified in terms of pull-in torque, which is generally the limiting torque, as pointed out by Mr. Rutherford. However, I believe locked-rotor current should be specified in amperes as at present; involving this specification with a value of torque can only be confusing to the power companies.

R. E. Hellmund (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): In Mr. Rutherford's paper and other papers,[1,2] motor applications are discussed in which the motor intermittently operates at relatively high load with prolonged intervening periods of no load or standstill. If in such cases the idle periods are relatively long compared with the operating periods, the root-mean-square load is, of course, well below the running load. On the other hand, the requirements for starting, pull-in, and pull-out torques are governed essentially by the character of the running load and therefore may have little relation to the root-mean-square load or to the continuous rating of the motor. Thus the latter obviously loses some of its practical significance and suggests the idea of making the pull-in, pull-out, and starting torques a more prominent part of the rating structure. However, while the conventional continuous rating in some cases loses in value on account of this, the motor temperature nevertheless is an important limiting factor in the operation of the motor. For this reason and also because rating by temperature-rise is so firmly established, it seems desirable to retain the temperature limits in some way or other as the basic factor for rating, but to supplement them by additional provisions for torque and starting-current values. Another reason for retaining temperature limits as a basic factor is that they are common to nearly all types of electrical apparatus, including generators, transformers, control devices, etc., while torques are of particular significance with motors only. It is believed that neither Mr. Rutherford nor the authors of the related papers previously referred to will disagree with this point of view, but their remarks might be misinterpreted because they have outlined methods for the application and selection of motors, in which, for practical reasons, the torque values are given consideration first and the temperature limitations are checked subsequently.

Figure 1



For some applications of motors, provisions for larger ratios of pull-in, pull-out, and starting torques have been made in the past and have been found to be a simple way out and one that is usually understood by everybody because it does not change the well-established basic method of rating but merely uses somewhat different ratios for certain torque values. When the load cycles are short, so that neither the motor nor any of the wiring or auxiliaries have a chance to vary much in temperature during the load cycle, there apparently is no reason for changing this well-established practice. However, there are some applications of motors with longer load cycles where the established practice would be satisfactory for the motor but where the heating effects might prove to be harmful to other parts of the circuit having a smaller time constant than the motor. This can best be illustrated by reference to figure 1 of this discussion. The condition shown here may be representative of a practical case of compressor equipment starting cold and requiring a heavy load during a prolonged pull-down period after installation or an extended shutdown such as referred to in Mr. Rutherford's paper. In the circuit of such a motor, there is always some likelihood of some parts (either the control or the wiring) having a much smaller time constant than the motor. In figure 1, curve *A* represents the time-temperature curve for the motor, while curve *B* is intended to apply to some part in the circuit or control having a much smaller time constant than the motor. In this case it has been assumed that during continuous operation both curves *A* and *B* reach a temperature-rise which is safe for continuous operation, as indicated by line *E*. It is further assumed that both the motor and the other circuit parts can be operated safely for short periods at a somewhat higher temperature, as indicated by line *F*. If we now assume that the load during the pull-down period is about 40 per cent higher than the rated load, it may well happen that the total motor losses, which are composed of constant losses and I^2R losses, will be increased by about 50 per cent, thus resulting in a time-temperature curve *C*. On the other hand, the other parts in the motor circuit represented by curve *B* may be heated by I^2R losses only, which with the assumed overload would then about double, and, furthermore, because of the small time constant of such parts, corresponding temperatures will be reached quickly, as indicated in curve *D*.

Examination of the figure shows that there are three distinctly different conditions. If the pull-in period is less than T_1, or about 18 minutes in this particular case, neither the motor nor other parts of the circuit will reach unsafe temperatures and no special precautions or change in practice seems necessary. If the pull-in period is very long, exceeding T_2, or about 103 minutes, both the motor and circuit parts will reach unsafe temperatures, which simply means that larger apparatus of higher rating has to be applied. If the pull-in period is between the values T_1 and T_2 shown in the figure, the application is perfectly safe for the motor but not for some of the circuit parts. Naturally, if it is desired to obtain maximum economy, the motor of the smaller rating can and should be retained, but the wiring or control apparatus, or both, for a motor of a higher rating will have to be used. This is the condition referred to in Mr. Rutherford's paper which is of interest not only to motor engineers but also to engineers interested in the power supply and auxiliary apparatus. It is for such conditions that it may be

advisable to give the motor a short-time or intermittent rating higher than its continuous rating, as this would then automatically lead to the proper selection of conductors and auxiliary apparatus.

The advisability of establishing intermittent ratings has, of course, been considered frequently, but so far no standard methods of rating along these lines have been established in the United States. As pointed out by Rutherford, the rather broad field of applications for refrigeration and air conditioning, makes a review of this problem in connection with standardization highly desirable if the best and simplest method for handling these applications is to be selected. Further study will be necessary to determine which method is best suited for this purpose and whether the standardization of certain intermittent ratings is more desirable. The application of motors in railway work has always been one of the most important examples of motors for intermittent operation, and here the problem has been solved in a practical way by assigning both a short-time (one hour) and a continuous motor rating. In view of the necessity for close application of apparatus in railway work, various methods for applying railway motors have been worked out. Therefore, it may be advisable to follow railway practice as closely as possible in some other applications. The proposal in a paper by Hildebrand[2] comes rather close to railway practice. Incidentally, a review of the methods of rating for intermittent loads seems timely, not only on account of the increased use of compressors for refrigeration, air conditioning, etc., but also because economic conditions surrounding these applications are different from those applying to other uses of motors for intermittent loads in industry. In many industries, the cost of motors and their power consumption is a very minor part of the total operating cost of such industries. Therefore, industrial engineers were perhaps inclined to do some overmotoring in doubtful cases because it gave them extra safety margins, which often were more important than maximum economy in first cost and operating costs. Contrary to this condition, the first cost and operating costs of refrigerating and air-conditioning equipment are an important factor to the owners of small commercial establishments or of homes, and in order to broaden the field of application, more attention may have to be given to economies possible.

While the condition illustrated in figure 1 may seem alarming, little trouble has been experienced in the past from overheating of circuit parts. Very likely the designers of control and other circuit devices have simply strengthened certain bottleneck parts whenever there was any indication of overheating in actual service. Some of this was perhaps also made necessary by the starting conditions of squirrel-cage motors. In other words, the co-ordination of the various parts of circuits has in the past been carried out successfully by providing rather liberal margins. If closer and more economical application of apparatus is to be accomplished, a more systematic co-ordination of standards will be necessary. Certain co-ordinating committees to be appointed by the AIEE standards committee will give this matter due consideration.

References

1. Rating of General-Purpose Induction Motors, P. L. Alger and T. C. Johnson. AIEE Transactions, volume 58, 1939, pages 445–59 (September section).

2. Duty Cycles and Motor Rating, L. E. Hildebrand. AIEE Transactions, volume 58, 1939, pages 478–83 (September section).

Paul H. Rutherford: Mr. Lukens has amplified the statements regarding the application of the motor to a refrigeration compressor on the basis of starting and accelerating torque but confines his comments to integral-horsepower capacitor motors which were not included in the paper. He does not state, however, whether he is referring to 40-degree or 50-degree-rise motors which is necessary when considering any torque comparison, between repulsion-start induction-run motors and capacitor motors. He states that the pull-up torque and starting current are the limiting factors which is not always correct as the starting torque of a capacitor motor is the limiting factor in most applications, particularly in the fractional-horsepower sizes. It is hard to agree with the value of 0.26 pound-feet pull-up torque per locked ampere for this reason.

It is certainly agreed that an inherent heating-overload protector is necessary and advisable on all capacitor-start motors for refrigeration applications but it is not yet fully determined that an automatic device is the best type and preferable to a manual-reset device on all sizes of motors. This will only be determined by experience. Mr. Lukens' statement that high maximum running torque is important does not coincide with his other statements and it will be found that in well-designed motors of either the capacitor or repulsion-start induction-run type there is ample maximum torque when the necessary starting and pull-up torque are obtained for the application.

Mr. Packer confines his comments to hermetically sealed compressors for commercial refrigeration use. It was not intended that the paper should include this type and we therefore, cannot see any direct bearing on Mr. Packer's comments on the paper.

Mr. Packer states that there is nothing to be gained by holding a standardized ratio of starting torque to horsepower. It was the author's point to try to select the horsepower as a ratio to the starting torque per ampere or the accelerating torques. We feel Mr. Packer has tried to apply the statements of the paper to sealed units. The paper did cover only belted units for commercial refrigeration and air-conditioning applications.

It is felt that all those discussing the paper with the exception of Mr. Fuller agree that a motor can be selected for a belted refrigeration compressor on a basis of starting and accelerating torque which Mr. Fuller states is impossible. He does not give any reason for selecting motors on the basis of maximum torque except that from the meager data on the experimental torque-recording device he speaks of, there is some evidence of the maximum torque being important. No specific sizes of compressors are mentioned but from the reference to a four-cylinder compressor it is probable that he is referring to a motor larger than five horsepower. It has been the experience of the author as well as many other refrigeration engineers after examining several thousand motors returned from the field during the last 15 years that failure of these motors was due to their not coming up to speed. This is evidence that these motors did not fail for lack of maximum torque but because of an insufficient starting or accelerating torque.

Mr. Fuller's comments on d-c or polyphase motors may be correct but these were not included in the paper.

Mr. Cain does not say whether the value of 26.9 amperes per horsepower is based on a 40-degree or 50-degree-rise motor. If this value is for a 40-degree motor, it is felt advisable to go to a 50-degree rather than raise the starting current limits as now used by the power companies.

Mr. Hellmund has commented on the intermittent character of the load taken by a refrigeration compressor. This is perhaps true of sealed-in units for household use but not so much with the conventional type unit as described in the paper.

Mr. Veinott's comments on the naming of the refrigeration unit by the horsepower rating of the motor was touched on slightly in the paper. Since current practice is to overload belted refrigeration motors to 50 degrees centigrade rise or more and successfully, it is felt that standards should be made that will acknowledge this fact. It was also suggested that since a refrigeration motor application is a "torque" application motor, torque should be tied up with name-plate horsepower stamping. It is felt that these two points are of utmost importance.

Mr. Veinott feels that the torques should be shown in per cent of full load torque rather than in pounds per horsepower. These figures seemed more convenient at the time but could be converted to percentages or ounce feet by simple arithmetic calculations.

Simplified Precision Resistance-Welder Control

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Synopsis: The types of resistance-welding applications requiring precision control heretofore characterized by electronic equipment are well-known. Attempts to extend the field of application to borderline operations have not met with complete success because of the initial expense and complicated nature of the control available. A simplified form of precision control consisting of a synchronized magnetic contactor and motor-driven timer overcomes these objections without compromise on results obtained.

ALTHOUGH many new types of spot-weld timers have been announced within the past two or three years, nearly all belong to a group that is characterized by a series of magnetic relays operated in conjunction with one or more time delay units of the electromagnetic, electrostatic, or mechanical types.[1] In each instance a magnetic contactor of considerable size is required to make and break the circuit to the primary of the welder transformer.

Relative simplicity and low initial cost have prompted the use of these nonsynchronous devices for all applications where extreme accuracy is not required. Operating limitations are well known and errors equivalent to *at least* a plus or minus one-half cycle of current are certain to occur although the actual timing period is perfectly metered. These errors result from inconsistent operation of standard a-c magnetic contactors and relays as well as more serious discrepancies introduced by failure to close and open synchronously the power line leading to the welder transformer.[2]

Effect of Nonsynchronous Control

The first specimen in figure 1 illustrates the effect of nonsynchronous control on welding of light-gauge stainless steel. Section *b* is a series of four good welds made with a regular load-current wave form and a one-half-cycle timing period. The welds are strong and the surface of the work is only slightly discolored. The welds in section *c* were made with the same pressure, current, and timing period but a transient wave form was obtained by changing the point on the reference voltage wave at which the welder transformer was energized. All four welds are overheated, testifying to the fact that the character of the wave form does affect the quantity of heat delivered to the weld. Section *a* contains a third group of four welds made on the same piece of work with equivalent current, pressure, and time setting. The power circuit was closed at a point which gave relatively normal wave form but it was opened slightly after zero, allowing nearly a full one-half cycle of arcing at the tips of the magnetic contactor. The overheated welds which resulted are a clear indication of the additional heat delivered to the work when an arc was allowed to occur as the power circuit was broken.

Assuming that an absolutely accurate timing period could be obtained with any one of the nonsynchronous units already mentioned, the variation in results evidenced by the three sections of specimen 1 could be expected. Of course, the effect of these variations is less noticeable when the nature of the work is such that longer timing periods can be used or the fusion point of the material is less critical. However, consistent results using a timing period as short as one-half cycle can be obtained when suitable synchronous control is used. Specimens 2 and 3 of figure 1 illustrate this fact in connection with 24-gauge stainless steel. Notice the consistency of the welds on specimen 2. Their strength is demonstrated by the "slug" of metal which has been pulled from specimen 3.

Figure 1. Stainless-steel specimens showing effect on weld of nonsynchronous control compared with consistent results obtainable when suitable control is used

Previous Synchronous Equipment

At least three general types of synchronous control equipment have been proposed to overcome the variations just described. The first of these—full electronic control using mercury-pool-cathode-type power tubes instead of magnetic contactors—has served its purpose well.[3,4] The chief objections are high initial cost as well as complicated operational and maintenance problems.

Synchronous-motor-driven contactors have also been offered as a solution.[5] Although reasonably priced, their adjustment is critical and difficult to maintain.

A more recent development is the so-called "impulse contactor."[6] Energy stored in a capacitor is discharged into the operating coil of a magnetic contactor causing its contacts to close and open at points determined by the inertia of the moving parts as well as the character of the contactor finger spring and

Paper number 39-65, recommended by the AIEE committee on electric welding, and presented at the AIEE winter convention, New York, N. Y., January 23-27, 1939. Manuscript submitted November 14, 1938; made available for preprinting December 29, 1938.

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1. For all numbered references, see list at end of paper.

the quantity of energy delivered to the operating coil. The equipment required involves considerable expense and the operating range is definitely limited. Proper adjustment is sometimes difficult because of the several related factors which influence the final setting.

Simplified Precision Control

This paper deals with a form of precision control unit consisting of a synchronous magnetic contactor and motor-driven timer. Two new developments make the system possible. The first is a special magnetic contactor consisting of two separately actuated poles connected in series (figure 2). One pole is closed early in the operating cycle. The closing of the second pole energizes the power circuit and opening the first de-energizes it. The actual period during which the transformer is energized is measured by the interval during which both poles are closed. Operating speed of the individual poles is not a limiting factor. Timing periods as short as one-half cycle are easily obtained.

The system just described is old but construction features of the contactors used are new. The closing contactor is adjusted to take advantage of a little-known operating characteristic. When properly designed a contactor's magnet coil can be energized at any point within a rather wide band and yet the tips of that contactor will close at essentially the same point on the reference voltage wave. The speed at which the contactor closes is influenced to a considerable degree by the amount of transient in the operating coil circuit. When correctly adjusted the energizing of that

Figure 2. Precision contactor consisting of closing and opening poles operated in sequence. Synchronizing equipment for opening pole is mounted on right-hand side of panel

circuit earlier than normal results in a decreased transient and a slower closing speed. Thus, the contact tips touch at a point equivalent to that of a much later energization of the coil circuit. Likewise, the increased transient which results from late energization of the coil compensates for the delayed start in that the contactor closes faster. This characteristic can be employed to insure consistent closing of the power circuit, thereby avoiding various degrees of tran-

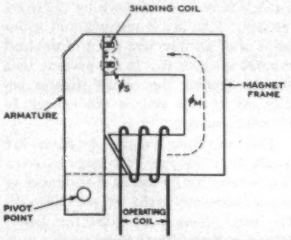


Figure 3. Sketch of magnet frame showing typical shading-coil circuit

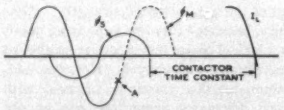


Figure 4. Phase relationship of main (ϕ_M) and shading-coil (ϕ_S) fluxes

sient and resulting variations in heat delivered to the work.

The opening contactor is self-synchronized to insure the parting of contact tips at the minimum arcing point. Because of the nature of the device there is no need for synchronous interruption of the contactor operating-coil circuit. Regardless of the time at which the circuit is broken the contactor opens at the point for which it is set.

Synchronous Magnetic Contactor

Synchronization to within a plus or minus ten electrical degrees or better is rather easily obtained by separately energizing the shading-coil circuit of the contactor. All a-c contactor magnets are equipped with a shading coil to insure quiet operation. The conventional design (figure 3) consists of a short-circuited turn of some conductive material encircling about two-thirds of the magnet pole face. Flux (ϕ_M) set up by the operating coil generates a voltage in the shading-coil circuit and the resulting current provides a flux (ϕ_S) which is out of phase with the parent flux (figure 4). If this supplementary flux did not exist the magnet surfaces of the contactor would part momentarily at each period

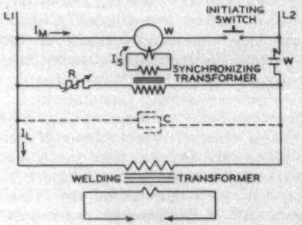


Figure 5. Schematic diagram of synchronized contactor circuit

during which the main flux passes through zero and an objectionable vibration would result.

By separately energizing the shading-coil circuit, synchronized opening of the contactor can be obtained without sacrificing quiet operation. Refer to the schematic diagram shown in figure 5. When the push button is closed the operating coil of contactor *W* is energized. The closing of the contactor energizes the welding transformer and simultaneously applies power to the primary of the small transformer which separately energizes the shading-coil circuit. Because of the difference in power factor between the operating-coil and shading-coil currents, the two out-of-phase fluxes necessary to quiet operation are obtained. Assume that the push button is released at the point marked *A* in figure 4. The main flux (ϕ_M) goes to zero but the shading coil flux (ϕ_S) is sufficient to keep the magnet surfaces sealed until it approaches zero value. Because the main flux is not there to supplement it, the magnet surfaces part. Although the shading-coil flux resumes in the negative direction before the armature of the contactor has moved enough to part the contact tips the contactor continues to open because the shading coil alone is not strong enough to reclose it.

The separately energized shading coil insures that the magnet surfaces always part at a point equivalent to the zero value of the shading-coil flux but the armature of the contactor must move an appreciable distance before the contactor tips part. The interval required for the movement is called the "time constant" of the contactor. Since the zero point of the load current bears no relation to the shading-coil flux the "time con-

stant" of the contactor must be equal to the difference in time between a zero point in the shading-coil flux and a later minimum value in load current. Adjustment can be made by changing wear allowance (sometimes called "follow-up") or spring tension. However, a more convenient method is available. A rheostat in series with the primary of the synchronizing transformer varies the voltage applied to it. The corresponding change in magnetizing current drawn by the transformer primary winding provides a variation in power factor of the shading-coil current. Since a phase shift of about 60 electrical degrees is practical with this method the "time constant" of the contactor can remain the same while the phase relationship of the shading-coil circuit may be changed to locate the minimum arcing point. Once adjusted, the contact tips part at the selected point independent of the time at which the operating-coil circuit is broken.

Many attempts to synchronize the opening of a power circuit in conjunction with magnetic or motor-driven contactors have failed because of a tendency for the arc to restrike after it presumably had been extinguished. The oscillograph trace represented in figure 6 indicates the voltage drop across the contactor tips. When they are closed only the reference line represented by the sweep of the oscillograph is recorded. As the tips part an arc is drawn and the drop across the arc is recorded in the form of a small voltage in phase with line current. When the load current passes through zero the arc voltage must also go to zero. Since the contact tips have actually parted prior to this time the oscillograph must instantly record line voltage across the gap. Such is the case in test *A*.

Figure 6. Oscillograms showing (A) arc interrupted, (B) arc restriking

For test *B* the contactor tips are parted at a point equivalent to that represented in test *A*. A similar arc voltage is recorded. It is reduced to zero with the load current. The voltage across the contact gap instantly approaches line voltage but the dielectric strength between the contact tips has not built up rapidly enough to resist breakdown by the rising voltage. The arc is restruck and maintains until another zero point of the load current is reached. It is apparent that merely opening the circuit slightly before the current zero is not enough to eliminate arcing.

Two solutions to this problem are available. The rate of voltage recovery can be retarded by means of resistance or capacitance connected in parallel with the load.[7] This delay gives the dielectric an opportunity to build up to a safe value. A second course of action is to alloy the contact tip material with elements intended to hasten the building up of the gap dielectric strength.[8] Mercury, because of its low vaporizing point, is a logical choice but it cannot be alloyed successfully with copper. However, cadmium, another choice of material with good deionizing properties, can be obtained in copper alloy form at reasonable cost. A combination of both corrective factors has proved to be the practical answer to the problem.

The synchronized magnetic contactor is an important development in connection with simplified precision control but it has an even broader field of application as an improved magnetic contactor for use with all kinds of welding machines involving heavy loads and frequent operation. The elimination of arcing at the contact tips overcomes the most pronounced limitation in contactor application. Mechanical life is above reproach but until now electrical ratings have been determined primarily by the heat liberated during the arcing period, and contact-tip life has been reduced proportionately. Figure 7 illustrates a 300-ampere (nominally rated) single-pole synchronized unit which has been successfully tested on a frequent operating cycle at 1,800 amperes, 220 volts, 47 per cent power factor.

Motor-Driven Timer

The second development contributing to the simplified precision control is a

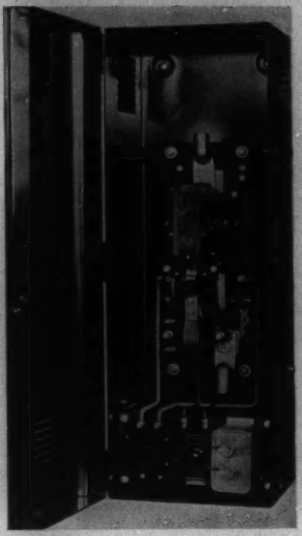


Figure 7. Single-pole 300-ampere (nominally rated) synchronized contactor for general application

new form of synchronous-motor-driven timer. Devices of this kind in the past have involved one of two distinct design problems. When a continuously operating motor was used, a magnetically operated mechanical clutch was required to begin and end the welding operation. Positive synchronization could not be maintained through such a mechanical linkage. When an attempt was made to start and stop the motor at the beginning and end of each operation, poor synchronization resulted because of the tendency to "hunt" on starting and to coast in stopping.

The motor of the timing device under discussion is allowed to run continuously but a clutch is not required. The schematic circuit diagram shown as figure 8 illustrates this fact. Although the pilot contact can be closed at any point, the cycle of operation is not begun until the cam actuated contact TR_1 is momentarily made, energizing synchronized contactor W_1 and control relay CR_1. Since TR_1 closes at only one point in the operating cycle, all timing intervals are measured from that point. Relay CR_1 forms a holding circuit about TR_1. Additional rotation of the cam shaft closes contact TR_2 which energizes contactor W_2 and completes the circuit to the welder transformer. Relay CR_2 is

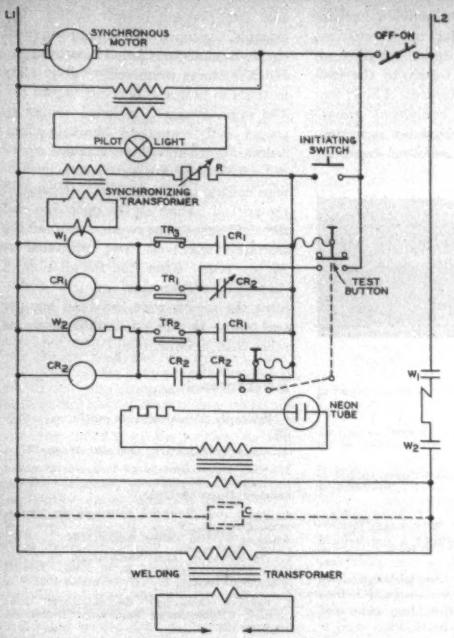


Figure 8. Schematic diagram of motor-driven timer circuit

closed at the same time to form a holding circuit around TR_3. Final rotation of the cam shaft opens contact TR_3 in the circuit to the operating coils of contactor W_1 and relay CR_1. The synchronized welder contactor then opens at the minimum arcing point. Relay CR_1 and contactor W_1 remain closed until the initiating switch is released. A normally closed contact on relay CR_2 prevents unauthorized repeat operation.

The weld period adjustment is made by turning knob C in figure 9. Its movement is transmitted through a pinion to a large gear on which contact TR_2 is mounted. The angular position of contact TR_2 with respect to the motor cam shaft determines the point at which welding contactor W_2 is closed. A pointer actuated by movement of the gear indicates the welding time selected.

Contacts TR_1 and TR_3 are mounted on steel plates which can be rotated manually to permit initial adjustment. Ball bearings are used throughout to insure precise operation for the entire mechanical life of the device.

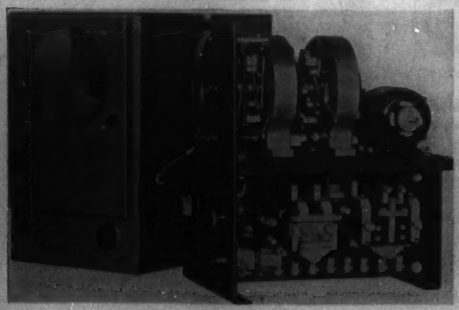
Figure 10 is a front view of the timer. A specially designed neon tube energized from a closely coupled transformer connected in parallel with the load indicates the exact welding time and assists in selecting the proper operating points for the magnetic contactors. During the period the welding transformer is energized, the bright glow of the tube is visible through a slot in the scanning disk which is attached to the end of the motor cam shaft. The resulting streak of light A includes dark bands as the supply line voltage passes through zero. Therefore, each section of the trace represents one-half cycle. Counting of the sections is not necessary since the timer dial is directly calibrated in cycles.

A test button B is provided to make possible repeat operation of the control equipment at a rate determined by motor speed. By closely observing the beginning of the light trace on dial as knob C is rotated, the stable operating point of the "closing" contactor can be selected prior to placing the equipment in operation. Proper adjustment will result in a consistent beginning of each successive trace.

Rheostat D is connected into the "opening" contactor synchronizing circuit and controls the point at which the contactor tips open. If the electrodes

Figure 10. Front view of motor-driven timer showing adjusting means and neon light trace on revolving disk

Figure 9. Timer with interior removed to show mechanical construction



of the machine are closed before the test button is operated the rheostat can be adjusted for minimum arcing before the welding operation is begun. Arcing will be indicated by an additional half-cycle band on the end of trace *A*.

Additional motor-operated contacts and a slight rearrangement of the circuit would permit the control of all four timing intervals (squeeze, weld, hold, and off periods) required in connection with fully automatic air-operated welding machines. Three knobs on the front of the panel would permit individual adjustment of all periods. The number of operations per minute is determined by the speed of the motor-driven cam shaft and could be varied by changing reduction gears between motor and cam shaft, by means of a simple transmission operated from the front of the panel. A dial calibrated in percentages and referred to the total number of cycles equal to a single revolution of the cam shaft at the prevailing speed would provide at a glance the relationship to each other of the component parts of the operating cycle.

The equipment just described is relatively inexpensive and easy to operate. Its mechanical construction is such that continued service without attention can be expected. One installation studied for a period of more than eight months was attended only by an untrained operator. Adjustments were readily made and no change was required until the end of the production run.

The accuracy obtainable with the simplified equipment is illustrated in figure 11. A cathode-ray oscillograph screen recording, in turn, the primary and secondary current wave forms of a welding transformer drawing about 300 amperes on the primary side was photographed at 30-second intervals during an 18-minute test. Throughout the entire operating period the circuit was established 150 times per minute for a duration of one cycle. The individual photographs apply in order to observations spaced 75 operations apart. Wave form and accurate timing testify to the consistent operation obtained. These features of the control equipment are responsible for the performance indicated:

1. Special magnetic contactor consisting of two separately actuated poles operated in sequence and having

(a). The circuit-closing pole adjusted to take advantage of natural response characteristic of the contactor.

(b). The circuit-opening pole self-synchronized to open at minimum arcing point independent of timer setting.

2. Motor-driven timer with a continuous-running motor but without a mechanical clutch.

3. Means for selecting the stable operating points of the magnetic contactors as well as determining the actual welding time and consistency.

Figure 11. Oscillogram showing accuracy of precision control equipment breaking a load equivalent to 300 per cent of contactor nominal rating

Conclusion

It is reasonable to believe that many welding operations made on machines not now equipped with precision control could be made much less expensive if proper control were installed. Likewise, many parts previously fabricated by other means could now be welded. Only the high initial cost and relative complexity of the control heretofore available has prevented such action. For example, a company manufacturing small circuit-breaker parts found it necessary to fasten contacts composed of silver alloy material to bronze connectors (figure 12). The same assembly included copper to copper and copper to bimetal joints. A motor-operated welding machine equipped with one of the better nonsynchronous control units was used. Because of the critical nature of the operation and the rigid inspection requirements of the assembly, rejections were estimated at 23 per cent. After the installation of simplified synchronous control equipment the rejects were less than one per cent and those were attributable to causes other than welding.

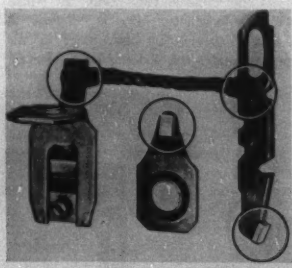


Figure 12. An assembly of small parts involving copper to copper, copper to bimetal, and copper to silver-alloy joints is successfully welded in production using simplified precision control

References

1. Welding Handbook, 1938 edition, pages 227–33.

2. Welding Handbook, 1938 edition, page 237.

3. New Developments in Ignitron Welding Control, J. W. Dawson. Electrical Engineering, December 1936.

4. Resistance Welding Improved by Thyratron Control, W. C. Hutchins. *Journal* of American Welding Society, August 1937.

5. Development and Application of Automatic Welding Control, H. W. Roth. *Journal* of American Welding Society, December 1933.

6. Impulse Operation of Magnetic Contactors, C. Stansbury. Electrical Engineering, May 1937.

7. Reignition of Metallic A-C Arcs in Air, Attwood, Dow and Krausnick. AIEE Transactions, volume 50, number 3, pages 854–70.

8. Extinction of Short A-C Arcs, T. E. Brown, Jr. AIEE Transactions, volume 50, number 4, pages 1461–5.

Discussion

L. G. Levoy and G. W. Garman (General Electric Company, Schenectady, N. Y.): Mr. Roby has given an interesting paper and has described an ingenious method of improving the accuracy of contactors as applied to resistance spot-welding machines. This improvement in accuracy should result in better welding from contactor-controlled machines and will expand the field of contactor control. The impression is given that this contactor is equivalent in price and accuracy to precision electronic control and that it is less complicated. Electronic control without question is more accurate and in most applications does not require any adjustments except for the occasional replacement of a tube, which can be quickly and easily changed. While it is true that some electronic controls are relatively more complicated, it is only because the demand has been such as to require the flexibility and accuracy which they provide.

With reference to these more complicated control circuits, it has been interesting to observe the trend in the various requirements with increased use and confidence in this type of control. Several years ago it seemed that the time had arrived for

simplification, but to our surprise accurate and consistent welding had led to the desire of welding methods and processes hitherto believed impossible or too expensive. This trend has led to the development of the interrupted type of welding and to the increased use of "heat control" by the phase-shifting method. In addition, there is a strong tendency toward the use of complicated time and heat control cycles. Thus the design engineer is faced with two conflicting trends, one toward simplification in an effort to reduce costs, which has led to the development of the ignitron contactor, and second, toward more flexible controls which inherently leads to higher costs.

The author states that the contactor tips open consistently within ten electrical degrees, but does not give specifically the accuracy of closing. It would appear that there are several factors which would affect the closing time and the opening time. It is expected that a reduction in line voltage would not only decrease the welding current in the normal manner but would retard the closing of the contactor, thereby reducing still further the welding current, particularly for short welding periods. Also, since the mechanical time constant of the contactor is fixed and does not necessarily agree with the power factor of the welder, a starting current transient may be present in the welding circuit. This transient is not necessarily detrimental, but will decay exponentially, producing variations in the current zero for different time settings. It is also well known that while the thickness of the material being welded does not affect appreciably the secondary current in low-power-factor machines, it does affect the power factor of the primary current. We would therefore like to ask Mr. Roby how critical is the adjustment of the shading-coil rheostat and what is the effect of these variations on this setting.

Variations in the phase angle of closure of the contactor tips with respect to the alternating voltage wave materially affect the root-mean-square current and therefore the heat delivered to the weld. The heat delivered to the weld is directly proportional to the resistance of the work, the time of application of the current, and to the square of the root-mean-square current. The magnitude of the variations in heat caused by small angular changes in the phase of closure can best be shown by a typical example as given in table I of this discussion. These results apply to a welder having a 0.30 power factor.

In this table, the angle of closure is measured from the power-factor angle. Positive angles are later in time corresponding to closure $^1/_{2\times 180}$ second too late on the wave. Negative angles correspond to closure too early by the same amount. In each case it is assumed that the contactor opens precisely at the current zero, so that the variations shown are entirely due to erratic closure of plus or minus ten electrical degrees. The heat delivered resulting from closure at the power-factor angle is taken as 100 per cent as a point of reference for each case. These variations, which amount to more than 50 per cent in the heat for a one-half-cycle spot length and 16 per cent for one-cycle spot length, are too large to be tolerated in many applications. In view of these variations, we would like to ask the author what precision, as regards phase angle of closure, can be maintained in practice with this device.

Furthermore, if the timing is adjusted for an odd number of half cycles, the resulting residual flux in the welding transformer may cause excessive sparking when the welding electrodes are lifted unless the shunt

Table I

Spot Length	Closure Angle, Measured From Power Factor (Degrees)	Per Cent Heat
One-half cycle	+10	73.1
One-half cycle	0	100
One-half cycle	−10	128
One cycle	+10	92.5
One cycle	0	100
One cycle	−10	109

capacitor, which is connected across the primary of the welding transformer, can absorb this energy or unless antipolar starting be used.

The oscillograms shown in figure 11 show a small discontinuity in the primary current wave such as might occur if the contactor bounced and arced, or started to drop out. Will the author please explain this discontinuity? Unfortunately, the scale of these oscillograms is so small that variations of current of a magnitude which might give unsatisfactory welding would be imperceptible.

One disadvantage of the motor-driven timer is that there is a variable time delay after the closure of the initiating switch before TR_1 closes, starting the cyclic process. The time delay depends upon the phase of closure of the initiating switch with respect to the position of the cam actuating TR_1. It may therefore be as great as one complete cycle of operation, or in other words the time delay may be as great as the time required to make a spot weld. In high speed production, allowance would have to be made for this maximum time delay, which may in some cases limit the rate of production. Electronic spot-welding control eliminates this variable time delay. In addition, electronic control permits the use of phase control, giving a smooth variation in heat without resorting to taps on the welding transformer. In many applications phase control has proved to be a most desirable feature. Contactor control eliminates the possibility of using phase control.

Because of its relative inflexibility and inaccuracy, this control is limited to certain spot-welding applications. Good seam welding requires more precise timing such as is obtained electronically because of the possibility of cumulative transients during the seam, so that the error may be much greater than the error of any single spot. Furthermore, because of life considerations, a contactor would not give adequate life on most production seam-welding jobs. Repeat operation is limited to the number of gear changes available. A recent control has been developed which provides the equivalent of at least 60 gear changes on this unit and maintains electronic accuracy. The cost of incorporating this large number of gears to make the device equivalent in flexibility with this new electronic control would probably be prohibitive. On many production jobs this great flexibility is not required. However, frequently production jobs change and it is obviously an advantage if the control is adaptable to any such possible change.

In closing, we would like to ask the author to present some actual life figures in terms of the number of operations possible. Operation in terms of time is of little value unless rate is also specified. Electronic controls have been in use for many years and the number of operations possible without changing tubes soars into astronomical proportions—hundreds of millions.

F. H. Roby: A discussion of the paper[1], "Simplified Precision Resistance Welder Control," prepared by D. G. Levoy and G. W. Garman, is typical of an attitude that has prevailed whenever magnetic contactors are mentioned with reference to accurate or precision control of a resistance weld. The author has no quarrel with electronic equipment. Such devices have, without question, performed to specification. Nevertheless, it is a fact that the least expensive standard electronic control costs more than many users are willing or able to pay. The result has been the continued use of nonsynchronous devices for applications where their inherent errors are objectionable. Since a device of the type described in technical paper 39-65 can be manufactured and sold for a price much less than that of the equipment now available, precision control can now be applied to more jobs.

It is true that an electronic tube is a simple switching device when judged by an electrical engineer. However, the typical electrician, maintenance man, or operator

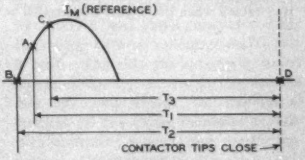


Figure 1

finds any electronic device something of a problem. When not understood, the very characteristics which seem simple to the engineer result in complications to the individual charged with using and maintaining the equipment. Because he is usually acquainted with mechanical motions and magnetic forces, a system composed of several such parts is readily understood and, therefore, simple. It will require many years of instruction to dispel this attitude.

Precision welding cannot be satisfactorily accomplished in the face of widely fluctuating line voltages. It has been stated by experienced users that ten per cent variation may seriously affect results. Standard contactors are equipped with magnet

coils designed to operate at 15 per cent under- and 10 per cent overvoltage. Welding contactors are equipped with intermittent duty coils that are even less affected by undervoltage.

Experience has indicated that a contactor can be closed more consistently than opened because of the stronger forces and faster accelerating rates involved. Using this experience as a basis, early investigators provided one normally open and one normally closed contactor operated in sequence respectively to close and open the circuit. Thus both functions were accomplished by energizing a magnet.

Accuracy in closing is improved considerably by utilizing the "flat operating characteristic" of a magnetic contactor. As pointed out in the paper, the closing speed of a contactor is influenced to a considerable degree by the transient drawn in its operating coil. Assuming a normal wave form, the pull of the magnet is proportional to the product of the pole face area and the *flux densily squared*. Under transient conditions the flux in the iron circuit may be as much as *double* normal value. Since the area of the pole face remains constant, the pull could be as much as four times normal. It is not difficult to believe that the closing speed of the contactor is changed accordingly.

Refer to figure 1 of this discussion for a graphic explanation of the "flat operating characteristic." Assume that the magnet is energized at point A on the coil current wave. A transient wave form will be obtained and the magnet pull which results will cause the contact tips to touch at point D. Time T_1 is consumed in closing. However, if the coil circuit is energized at point B no transient exists and the lessened pull causes the contactor to require T_2 time for closing thereby compensating for the early coil energization. Likewise, energizing the coil circuit at point T provides a greater transient and increased pull. Closing time T_3 results, thus compensating for the late energization in the magnet circuit. Proper adjustment of the closing contactor is obtained when its magnet is energized at point A (the middle of a 60-electrical-degree band). The neon tube indicator assists in obtaining the correct setting.

Under perfect operating conditions there will be small variations in the closing point. However, large-scale oscillograph records indicate that these are not enough to affect results in most instances. The oscillogram reproduced as figure 11 is not enlarged enough to serve this purpose but it does indicate a consistent wave form which, in turn, is the result of consistent operation. The small "break" in the oscillograph trace is caused by contact tip bounce in closing. This bounce is the result of energy stored in the contact tip and is characteristic of all magnetic contactors.

The tips of the opening contactor are usually set to part at a point approximately 30 electrical degrees before current zero. Because the current value is rapidly approaching zero, no appreciable arcing can be noticed. Assuming a ±15-electrical-degree error under the least favorable operating conditions, the power factor of the load would be required to increase from 50 per cent to 80 per cent to cause arcing. A decrease in power factor would have no effect other than to cause the tips to open slightly higher on the current wave, thus drawing a little more arc. The adjustment is not critical.

An odd one-half cycle is included in the time required for the timer cam shaft to make one revolution thus giving the effect of antipolar starting.

The elimination of a mechanical clutch in the timer system through the use of an "initiating relay" has introduced a variable time delay in starting the weld. This delay is objectionable only when extremely high production rates are involved. Since most precision jobs are necessarily of low production because of care in mechanical alignment and frequent dressing of electrodes, this objection is not a valid one. It would be possible to employ a clutch in the system without materially affecting the accuracy of the timer but the advantage gained does not warrant the introduction of an additional mechanical link.

The authors of the discussion are under the mistaken impression that mechanical equipment is to be recommended for seam welding. A satisfactory seam weld may require from 10 to 16 interruptions per inch. Assuming a feed rate of 90 inches per minute, the equipment would be required to operate at the rate of from 900 to 1,440 complete cycles per minute. Mechanical contactors should be limited to about 400 operations per minute since their mechanical life is determined somewhat by the speed at which they operate. Thus seam welding is not considered a suitable field of application.

Heat control is of value on some applications where extremely fine increments of adjustment are desired. The many applications falling outside of this group represent a field broad enough to justify the development of a precision controller which does not include the heat-control feature.

Magnetic contactors designed for welder service have long since been perfected to the extent that service in excess of 15,000,000 operations is obtainable without prohibitive maintenance. Under severe operating conditions automobile plants use the same equipment for several programs. In lower-production shops the contactors will serve indefinitely. It is only natural that concerns recently associated with electronic devices are not acquainted with current contactor performance data.

A fully automatic welder control unit is practical without considering 60 gear changes. Flexibility of the type mentioned would probably be necessary in connection with a laboratory installation but normal production facilities would involve only six or eight.

Experience over the past 18 months has demonstrated that many difficult welding jobs can be readily accomplished with the equipment under discussion. It is not intended that it be used to the exclusion of all other types of control. Instead, it should be considered as a supplement to control now available, bringing into reach of the average user the advantages of precision control.

Load Ratings of Cable

HERMAN HALPERIN
MEMBER AIEE

Synopsis: Operating and test data concerning the maximum safe loading of impregnated-paper-insulated lead-covered cable are presented. The results of the study may be summarized as follows:

1. The occasional operation of cable at higher temperatures than are permitted by present temperature rules effects considerable economy.

2. During emergencies, temperatures of 5 to 35 degrees centigrade (depending on kind of cable) above those permitted by the rules are safe for the insulation.

3. For extra-high-voltage solid-type cable, void formation in insulation and expansion of lead sheaths may limit allowable temperatures and temperature ranges.

4. Cracking of lead sheaths due to reciprocating cable movement into manholes may limit the temperature range for usual daily loading. Limitation is more severe for longer conduit lengths up to 500 feet, but changes little with increase from 500- to 1,000-foot lengths.

5. Cracking of sheaths in manholes due to cable movement may be reduced by improving manhole conditions.

6. For many cables a balanced design requires a lead-alloy sheath that gives increased resistance to effects of cable movement and of internal pressures.

7. Continuous field temperature surveys are essential to efficient use of large conduit and cable systems.

8. Only a small fraction of the cable ever operates at the higher temperatures.

9. Data on center empty-duct temperatures and on average heat losses over 24-hour periods give satisfactory results in heat calculations.

10. Other practices which increase load ratings are the use of different ratings for various periods of the year, the replacement of poor soil in special cases, and the use of extra-large conductors in warmer conduits.

THE PURPOSE of the investigations covered in this paper has been to obtain the most efficient use of impregnated-paper-insulated lead-covered cable and accompanying conduits and manholes. Using considerable recent data, the author has attempted to cover in one study all important factors affecting load ratings.

With the sharp improvements during the past 20 years in the quality of cable and joints and in their installation and maintenance, there has been an accompanying sharp decrease in the rate of failures; for example, during the past 15 years in Chicago the total rate of failures of 12-kv lines consisting of 500,000-circular-mil three-conductor 13-kv belted cable has decreased from about 40 failures to 5 failures per hundred miles per year. At the same time, the quality of terminal equipment has improved greatly. These trends show a sharp decrease in the frequency with which low- or high-voltage circuits are being subjected to loads approaching their maximum ratings on account of outages of parallel circuits.

The outgrowth of these improvements, together with new knowledge on the effects of high temperatures on cable and joints, has been the definite establishment during 1930–37 of emergency load ratings for cable in Chicago operating from 120 volts to 132,000 volts. Generally emergency ratings determine, with the exception of the 120-volt a-c network cables, when additional underground circuits must be installed.

If, for example, the maximum rating of 500,000-circular-mil three-conductor 13-kv cable is increased by 15 per cent by allowing temperatures to exceed occasionally the maximum given in AIEE standards,[1] then on a growing system large reductions in the immediate and future investments needed for additional circuits and conduit will be obtained. With the increases in copper losses, in dielectric losses, and in maintenance costs at the higher loadings taken into account, the net reduction in total annual investment and operating charges per kilovolt-ampere mile for installed cable and conduit would be 9 per cent, assuming that the higher temperatures did not cause the cable life to be less than would be required from the standpoint of obsolescence and system changes. The increased ratings might be obtained on future lines without exceeding the maximum temperature given in the standards by using 650,000- instead of 500,000-circular-mil cable, but the total annual charges per kilovolt-ampere mile would then be reduced only one per cent.

On account of the use of items having standard ratings, terminal equipment frequently can safely carry more load than the cable connected to it. Increased load ratings of cable, therefore, produce substantial reductions in the cost per kilovolt-ampere carried through such equipment. An important overall advantage is obtained by higher loading in reducing the space required in the streets for conduits and at stations and substations for terminal facilities.

Various aspects of the problem of load ratings are discussed in four divisions of the paper:

Part I—Limitations due to the insulation

Part II—Limitations due to the sheath

Part III—Heating characteristics of conduits

Part IV—Principles and methods of calculation

Part I. Limitations Due to the Insulation

Since 1925 the maximum allowable operating temperature for solid-type impregnated-paper insulation has been 90 degrees centigrade minus the rated voltage in kilovolts, with a maximum of 85 and a minimum of 60 degrees centigrade. For multiple-conductor belted cable the rated voltage between conductors, and for shielded and single-conductor cable the voltage between conductor and sheath is used. This rule was apparently based on the following: above 85 degrees the rate of deterioration in mechanical strength of the paper increases rapidly with increasing temperature; as the operating voltage increases, the stress, and hence the probability of serious ionization, increases.

When this AIEE temperature rule was first established (then it was 85 degrees minus the rated voltage), ionization had not been recognized, and means to measure it were not available. At that time the reason for the decrease in temperature with increase in voltage was that the dielectric losses for high-voltage cables increased rapidly to very high values with temperature and increased the possibility of cumulative heating. For over 12 years, impregnating compounds which give small dielectric losses have been in use.

Paper number 39-29, recommended by the AIEE committee on power transmission and distribution, and presented at the AIEE winter convention, New York, N. Y., January 23–27, 1939. Manuscript submitted October 22, 1938; made available for preprinting December 15, 1938.

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The author is very grateful for the assistance received in the preparation of this paper and wishes to make the following specific acknowledgments: part I, H. A. Adler, C. E. Betzer, and O. B. Turbyfill; part II, M. C. Hedges, H. J. Plumley, and F. O. Wollaston; parts III and IV, C. A. Bauer and D. D. Nagley.

1. For all numbered references, see list at end of paper.

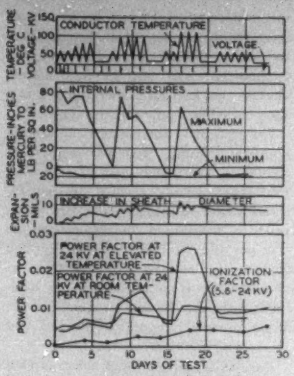


Figure 1. Aging test of sample F (three-conductor 13-kv cable)

The rate of deterioration of paper at various temperatures has been investigated by Massachusetts Institute of Technology,[2,3,4] H. W. Fisher and R. W. Atkinson,[5] F. M. Clark,[6] and others in individual tests varying from ten days to 17 months. The results are in agreement in showing that heat above 85 degrees centigrade causes an appreciable decrease in tensile and tearing strength of paper, but that the dielectric strength is not influenced much until the mechanical strengths have been almost destroyed. The main consideration, therefore, is the influence of heating on the ability of the cable to withstand removal and reinstallation without material lowering of the dielectric strength of the cable.

Experience, supplemented by careful examinations, has shown that the mechanical properties of the insulation of cable that has been in service in Chicago up to 40 years are sufficient to permit withdrawal of the cable and its successful operation after reinstallation, except in the few cases where the maximum temperatures have substantially exceeded the limits given herein for emergency operation. The cable, however, is gradually scrapped before the useful life of the insulation has expired due to (1) refitting to other locations on the system, (2) elimination of sheath damages, and finally (3) obsolescence. Serious deterioration due to ionization has been found mainly in poor high-voltage solid-type cable made 12 or 15 years ago; this has been due mainly to factors other than operating temperatures. Evidently the maximum use of the cable was usually not being obtained, because the loading was insufficient.

The temperature rule makes no provision for increased loads in emergencies for periods of one or two days. Therefore, sufficient carrying capacity needs, under the rule, to be installed so that in the worst expected emergencies the hottest part of the cable in the circuits remaining in service will not exceed the prescribed temperature. Obviously, then, almost all of the cable will be operating far below the temperature limits for the great majority of the time. For example, for the 1,030 miles of three-conductor cable operating at 12 kv in Chicago in 1937, 95 per cent operated up to a maximum of 60 degrees or less, 4 per cent up to 70, and the very maximum was 82 degrees centigrade or only 5 degrees above the temperature given by the rule. For each length of cable, the average temperature for the year was usually 15 or 20 degrees less than the annual maximum. Due to the new emergency ratings, it is expected that in the future the temperatures will range to higher values.

It is, therefore, economical to take some chances of exceeding the limits in AIEE standards for a few hours or so during an occasional emergency in order to utilize efficiently the entire system, with the understanding that it might result in shortening seriously the life of the insulation of one or two per cent of the cable.

Tests[4] have shown that the wood-pulp paper available for cable insulation in 1926 deteriorated in mechanical strength less than about five and ten per cent in 50 hours at, respectively, 120 and 140 degrees centigrade and showed no change in electrical strength. Tests[5] reported in 1921 showed that Manila papers in use at that time deteriorated with heating only slightly more than those tested in 1926 and much less than those tested in 1905.

Wood-pulp paper, which began to replace Manila paper about 1924, is used almost entirely now. Marked improvements have been made in it for electrical insulation since 1926. The tearing and dielectric strengths increased by about 50 per cent. In addition, improvements have been made in the application of the paper. Thus, paper in recently-made cables may be permitted much greater percentages of depreciation due to heating than paper in earlier cable before the cable becomes unfit for reinstallation. The available information indicates that recently-made paper may be safely operated about 15 degrees centigrade higher than 1920 paper and about 30 degrees higher than 1905 paper.

In general, the subsequent discussion on maximum allowable temperature refers to the temperature for the cable in the

Table I. Tests on 500,000-Circular-Mil Three-Conductor Belted 13-Kv Cable With Pressure-Tight Potheads

Sample	*A*	*B*	*C*	*D*	*E*	*F*	*G*
Year made	1924	1925	1928	1937	1937	1937	1938
Service before test (years)	13	12	9	None	None	None	None
Compound	Petrolatum	Petrolatum	Rosin-mineral oil	Rosin-mineral oil	Mineral oil	Mineral oil	Rosin-mineral oil
Power factor at 13 kv and room temperature							
Initial	0.0036	0.0077	0.0042	0.0029	0.0026	0.0043	0.0040
After 60- and 80-deg cycles	0.0052	0.0069 (0.0095)	0.0043	0.0077 (0.0086)	0.0031 (0.0033)	0.0060 (0.0071)	0.0049
After 100-deg cycles	0.0057	0.0085	0.0049	0.0099	0.0037 (0.0048)	0.0074 (0.0089)	0.0067 (0.0076
After 115-deg cycles			0.0048 (0.0050)	0.0218	0.0074 (0.0087)	0.0093 (0.0109)	0.0073
After final 60-deg cycles			0.0047	0.0089	(0.0085)	0.0085	0.0052
Power factor at 24 kv and room temperature							
Initial	0.0098	0.0086	0.0043	0.0032	0.0027	0.0046	0.0055
After 60- and 80-deg cycles	0.0122 (0.0199)	0.0137 (0.0272)	0.0088	0.0106 (0.0135)	0.0031 (0.0035)	0.0061 (0.0072)	0.0049
After 100-deg cycles	0.0120 (0.0183)	0.0181 (0.0182)	0.0094	0.0129 (0.0155)	0.0044 (0.0074)	0.0078 (0.0089)	0.0074 (0.0077)
After 115-deg cycles			0.0099 (0.0117)	0.0302	0.0138 (0.0152)	0.0100 (0.0109)	0.0110 (0.0207)
After final 60-deg cycles			0.0095	0.0113	0.0137 (0.0168)	0.0105	0.0081
Power factor at 24 kv and 60 degrees centigrade							
Initial	0.0137	0.0563	0.0084	0.0038	0.0026	0.0041	0.0032
After 60- and 80-deg cycles	0.0153	0.0400	0.0100	0.0061	0.0031	0.0050	0.0043
After 100-deg cycles			0.0107	0.0069	0.0035	0.0055	0.0045
After 115-deg cycles			0.0125	0.0090	0.0062	0.0079	0.0065
After final 60-deg cycles			0.0123	0.0083	0.0101	0.0078	0.0063

NOTES: Figures in parentheses are maximum values reached in the test period. Samples *A* and *B* failed at low temperatures after the 100-degree cycles.

Table II. Tests With Pressure-Tight Potheads—Maximum Pressures

Sample	A	B	C	D	E	F	G
Maximum pressure (pounds per square inch)	6	92	85	58	110	83	107
Cycle number	10	3	1	2	1	1	7
Temperature at which maximum pressure occurred (deg C)	100	75	58	60	60	60	99

hottest conduit section along a circuit during an emergency of a day or two every year or few years, it being known that the temperatures of the remaining conduits will usually be 5 or 10 or even as much as 20 degrees centigrade lower, and that the usual cable temperatures will be materially less than the maximum permitted by existing rules in the United States.

Limitations for Low-Voltage Cable

For cable operating at 7,500 volts and less, the electrical stress is so low that the deterioration of the insulation from the standpoint of electrical strength at temperatures up to limits of 82½ to 85 degrees centigrade set by the temperature rule is practically impossible. Since the stresses are low, there is no problem of dielectric losses.

Large amounts of cable have been in operation for 25 years or more at about 120 volts in Chicago and elsewhere, and much of it has operated at temperatures up to 105 degrees centigrade or more without serious effects on the insulation. Due to effects of the World War, carrying capacity was inadequate in Chicago for five years. During this five-year period, about 15 per cent of the two-conductor concentric cables were operated at least once a year at conductor temperatures above 125 degrees centigrade, and about seven per cent exceeded 125 degrees regularly with temperatures of 9 to 25 degrees centigrade less for the outer insulation. Some of the cable operated with copper temperatures over 200 degrees. Although the inner tapes in the insulation of some of this cable were greatly weakened, the outer tapes were almost invariably in fair condition and did not preclude successful use on reinstallation. During the past 35 years, several per cent of the 1,500,000-circular-mil single-conductor cable has operated at times at temperatures of 110 to 135 degrees centigrade without interfering with its continued operation or with its reuse after removal.

Proposed standards for this country set maximum hot-spot copper temperatures of 95 and 105–115 degrees centigrade, respectively, for continuous and emergency operation of transformers of any voltage. Even higher temperatures for emergencies have been proposed by one manufacturer[7] for transformers having an inert gas over the oil and by some operators for all transformers.

All factors considered, it seems that a reasonable limit for the insulation of low-voltage cable for emergency operation is 105–120 degrees centigrade. For so-called continuous loading, the limit should be 85–95 degrees, depending on how often and long the cable operates at the maximum temperatures.

A somewhat similar conclusion was discussed[8] before the AIEE in 1921 and was generally acceptable for practical use. The necessity for emergency operation was admitted, but some of the discussers were reluctant to provide for it in the rules. It appears that the insulation of cable manufactured during at least the past 12 years can successfully withstand operation up to the suggested limits.

Limitations for Three-Conductor 7.5- to 15-Kv Cable

Half of the high-voltage cable used in this country is three-conductor belted cable operating at 7.5 to 15 kv. For three years the Commonwealth Edison Company has been conducting accelerated aging tests on such cable to determine the effects of rare overloads on the cable on its 9- and 12-kv systems. Fifteen samples representing new cable and cable removed from the system and made by various manufacturers have been tested to the time of writing. The effective test length was usually a little over 100 feet and ended near the crotch in each pothead.

The first eight samples had test terminals filled with heavy compound exposed to open air. These terminals were not effective in preventing migration of the filling compound into the cable and did not allow the development of high pressures and vacuums in the cable.

Conditions in the middle of long lengths of cable between manholes were simulated in tests with pressure-tight terminals on the next seven samples. The amount of filling compound was reduced as much as feasible, that is, to 0.4 gallon per terminal. The terminals were filled completely with a heavy mineral oil as used in solid-type cable.

The test consisted in the application of a continuous overvoltage with superimposed heat cycles. The test voltage has been 24 kv, three-phase, 60 cycles for all samples except two. The heating was done by induced current through the three conductors, each conductor forming a one-turn short-circuited secondary on iron-core transformers placed around the samples. Heating current was applied daily for eight hours, except on Saturdays and Sundays, with cooling in open air. The nominal maximum copper temperatures began at 60 and increased as the testing proceeded to 115 degrees centigrade. After each set of high temperature cycles, one or more cycles of heating to 60 degrees were introduced to determine the effects of the higher temperatures on the normal operating characteristics, 60 degrees representing a high value of normal maximum temperatures. The duration of the aging tests was usually four weeks.

During the aging tests, measurements were made daily of power factors at test

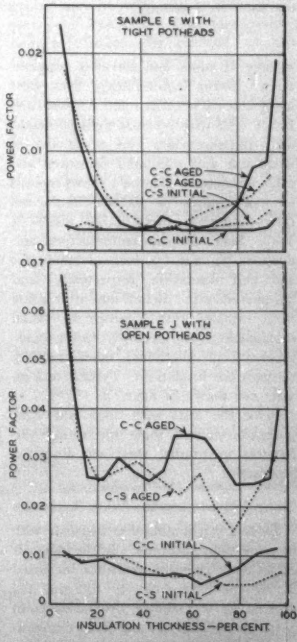


Figure 2. Changes in radial power factor at 60 degrees centigrade for 13-kv cable in accelerated aging test

C-S—Conductor to sheath
C-C—Conductor to conductor

Table III. Tests With Pressure-Tight Potheads —Pressures and Sheath Expansion

Sample	Start	After 80-Deg-C Cycles	After 100-Deg-C Cycles	After 115-Deg-C Cycles
Maximum pressures during 60-deg-C cycles*				
A	0	− 4		
B	42	− 5		
C	85	8	8	6
D	58	18	3	−10
E	110	11	5	− 4
F	83	1	−12	−16
G	57	4	− 5	− 5
Minimum pressures during 60-deg-C cycles (inches of mercury)				
A	−27	−17		
B	−10	−17		
C	−18	4	− 2	− 2
D	−30	−25	−28	−28
E	−20	−23	−27	−22
F	−13	−18	−19	−19
G	−18	−22	−24	−24
Increase in cable diameter at room temperature (mils)				
A		2	2	
B		6	12	
D		5	12	15
E		12	18	24
F		4	7	8
G		2	6	8

* Pressures (positive values) and vacuums (negative values) are, respectively, in pounds per square inch and inches of mercury.

voltage at room and elevated temperatures. Power factor-voltage tests were made twice a week at room temperature. In the tests with pressure-tight potheads, daily measurements were made also of maximum and minimum pressures and cable diameters. Figure 1 shows records for one sample of 500,000-circular-mil three-conductor 13-kv cable made in 1937. Such cable has sector-shaped conductors, $^{3}/_{64}$ and $^{5}/_{64}$ inch of conductor and belt insulation, respectively, and $^{9}/_{64}$-inch sheath. Before and after aging tests, samples were obtained for visual examinations and for power factor measurements of individual tapes radially through the insulation. Typical test results are shown in figure 2.

Since the tests with open and tight potheads showed some interesting differences in results, they are discussed separately.

Tests With Pressure-Tight Potheads

Table I is a summary of the tests with pressure-tight potheads. In the four new cables made recently, ionization increased during the load cycles to 100 and 115 degrees as was shown by increases in power factor at 24 kv and room temperature of 0.0063 to 0.0270 and by development of some carbon in the compound at the center of the cable. However, in subsequent cycles to 60 degrees considerable recovery in power factor occurred. Similar cables made 12 or 15 years ago have sometimes shown similar changes in normal operation. Three of the tested samples have been placed in service at 12 kv to verify over a period of years the conclusion that they will still operate satisfactorily.

One of the test samples was from 1928 cable which had been in service for about nine years, during which considerable deterioration had occurred. Although some further deterioration developed in the aging tests, the changes were not so great as those in the four new cables.

Two cables containing petrolatum, made in 1924 and 1925, had been in service for 12 to 13 years. Ionization increased considerably in both of these cables in load cycles to 60 and 80 degrees, and both failed at low temperatures after the end of the series of 100-degree cycles.

The outstanding point in these data is that, although ionization increased in all samples, the changes in power factor at rated voltage were usually small, indicating that, even if void spaces are created, little ionization occurs at normal voltage. In general, the first cycle of each temperature step seemed to have the greatest effect. An exception is the maximum power factor at 13 kv of 0.0218 for sample *D*, which occurred after cooling from 115 to 21 degrees. Such severe temperature changes will never occur in service. Furthermore, this sample recovered in subsequent 60-degree cycles so that the power factor decreased to 0.0089.

The changes in solid losses (losses in impregnated tapes only) were of minor importance compared with the increases in losses due to gaseous ionization. The power factors at room temperature and 5.6 kv increased during aging by 0.0006 to 0.0077. As table I shows, the changes in power factor at 60 degrees were moderate. Also, the radial power-factor curves obtained before and after aging showed small changes except near copper and lead. The changes in the average of the radial power-factor curves before and after aging ranged from a decrease in power factor of 0.0127 to an increase of 0.0039.

Maximum pressures as high as 110 pounds per square inch were observed. As indicated in table II, the maximum pressures did not occur at the highest temperatures. Four of the samples developed maximum pressures in the initial 60-degree cycles; none in the 115-degree cycles. The maximum pressures were apparently determined by the increase in maximum temperature over the highest previous temperature level rather than by the absolute values of the maximum temperature.

The maximum pressures decreased sharply in succeeding heat cycles at the same temperature due to expansion of the sheath. Table III shows how the maximum pressures decreased in the 60-degree cycles at various stages of the test. For the four new cables, *D*, *E*, *F*, and *G*, the pressures did not become positive at any time during the series of final 60-degree cycles, although for cable *E* this final series lasted four weeks. The minimum pressures showed little change during the aging tests in spite of the sheath expansion.

These pressure data suggest that emergency loading causing temperatures up to 100–115 degrees are not likely to produce much higher pressures than occur in the early stages of usual operation, especially since the cable will have probably carried a good load prior to the emergency. The data further indicate

Table IV. Tests on 500,000-Circular-Mil Three-Conductor 13-Kv Cable With Open Potheads

Sample	*H*	*I*	*J*	*K*	*L*
Year made	1923	1924	1927	1935	1936
Service before tests (years)	13	12	5	None	None
Compound	Petrolatum	Petrolatum	Rosin-mineral oil	Rosin-mineral oil	Mineral oil
Maximum temperature reached (deg C)	117	107	118	120	111
Power factor at 13 kv and room temperature					
Initial	0.0062	0.0047	0.0050	0.0052	0.0037
Maximum	0.0098 (103)	0.0138 (107)	0.0080 (118)	0.0099 (83)	0.0052 (111)
Final	0.0082	0.0122	0.0080	0.0084	0.0048
Ionization factor (5.6-24 kv) at room temperature					
Initial	0.0040	0.0086	0.0042	0.0008	0.0041
Maximum	0.0088 (103)	0.0202 (62)	0.0127 (118)	0.0195 (104)	
Final	0.0028	0.0024	0.0060	0.0030	0.0003
Power factor at 24 kv and 60 degrees centigrade					
Initial	0.0353	0.0159	0.0154	0.0078	0.0039
Maximum	0.0390 (103)	0.0588 (107)	0.0375 (118)	0.0277 (104)	0.0242 (111)
Final	0.0370		0.0221	0.0137	0.0214

Note: Figures in parentheses show maximum temperature in degrees centigrade after which power factor shown occurred.

the overloads will not make the vacuum after cooling more severe.

Tests With Open Potheads of Cables Made After 1920

In contrast to the tests with pressure-tight potheads, none of the cables tested with open potheads failed or showed signs of approaching instability. No high pressures or low vacuums occurred in these samples. Table IV summarizes the test results. Although the heat cycles produced some increases in ionization factor, the final values were low. The maximum ionization factors did not occur in most cases after the highest temperature steps. It appears that the decrease in viscosity of the pothead compound at the higher temperatures favored migration of compound and reimpregnation of cable insulation near the ends of the samples. For sample *L* the ionization factor was highest at the start.

The solid losses increased in all cases. In sample *L* the increase in power factor was mainly caused by the unusual migration of asphaltic compound from joints in the test leads for at least 20 feet into the test length. For other samples, the increases in power factor were probably caused mainly by deterioration at the high temperatures. The increases during aging in the average of the 60-degree power factors of the individual

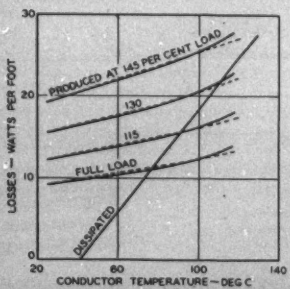


Figure 3. Thermal stability of used 500,000-circular-mil three-conductor 13-kv cable

Solid curves—Sample *J*, rosin-mineral compound cable made in 1927

Dashed curves—Sample *H*, petrolatum-compound cable made in 1923

tapes varied from 0.011 to 0.115 for four samples. For the fifth sample the average of the radial power-factor curves after aging was 0.022 less than before aging, but this difference was due probably to longitudinal nonuniformity of the quality of this sample of used cable.

Table V. Aging Tests of an Old Rosin-Impregnated Three-Conductor Cable

Approximate Maximum Temperature (Deg C)	Number of Cycles	Power Factor at Room Temperature and 15 Kv		Ionization Factor (5.6–20 Kv)		Power Factor at Elevated Temperature	
		Start	Maximum	Start	Maximum	Start	Maximum
80	4	0.0095	0.0167	0.0107	0.0121	0.224	0.224
80	5	0.0112	0.0309	0.0075	0.0173	0.353	0.388
90	5	0.0131	0.0148	0.0163	0.0216	0.429	0.479
60	5	0.0142	0.0146	0.0208	0.0184	0.209	0.233
100–110	5	0.0145	0.0198	0.0184	0.0330	0.550	0.636
60	2	0.0187	0.0185	0.0326	0.0319	0.334	0.334

These data indicate that the changes in solid losses, even where considerable migration of asphaltic compound into the cable occurred, are not serious enough to cause failures in service, except possibly in some rare instances.

Tests With Open Potheads of Old Rosin Cables

Aging tests were made of three samples of cable made prior to 1920. They had round conductors and $^{13}/_{64}$- and $^{9}/_{64}$-inch rosin-impregnated conductor and belt insulation, respectively. One sample of 250,000-circular-mil cable failed in the first cycle after having been subjected to 24 kv for $2^{1}/_{4}$ hours and having reached a copper temperature of about 60 degrees. Another sample of similar cable withstood 36 days at 15 kv but showed considerable increases in power factor and especially in ionization factor after the first 80-degree cycle, as shown in table V.

The third sample, having number 4/0 conductors, showed signs of serious instability in the first 60-degree cycle at 15 kv, the power factor at elevated temperature rising from 0.20 after six hours of heating to nearly 0.70 after about seven hours of heating. The voltage was therefore reduced to 12 kv. The cable failed at elevated temperature in the fourth 60-degree cycle.

The two failures in this group of tests were apparently caused by thermal instability due to high dielectric losses. The impregnation of these cables was poor. The older cable, as represented by these two samples, is not considered suitable for reinstallation on the 9- and 12-kv systems, while somewhat similar cable made later (1912–18) has been so satisfactory that it is being reinstalled.

Thermal Stability

The thermal instability just discussed raises the question of instability due to overloads in service. Figure 3 shows thermal stability diagrams for two cables removed from service. The curves represent the total watts generated in the cable at various loads at operating voltage. The straight line shows the total watts which can be dissipated assuming at the start a summer duct temperature of about 40 degrees, no load for the cable in question, and usual loading for the other cables in the conduit. The intersections of the curves with the line give the copper temperatures reached for one-day emergency loads. In deriving the curves, the author has in each case used unfavorably high values of power factor in order to take into account the effect of deterioration due to aging during the overloads.

The diagrams show that such used cables are thermally stable even at 30 per cent overload. The approximate copper temperatures reached at full load, 15 per cent overload, and 30 per cent overload, respectively, are 77, 90, and 110 degrees. Lower duct temperatures would move the straight line to the left, and correspondingly higher loads would be permissible. It is of interest that, even if a power factor of about 0.20 is reached at a temperature of 115 degrees, the dielectric losses on these cables would be only seven per cent of the copper losses.

Assuming a base duct temperature of about 40 degrees, even old rosin cables would probably be thermally stable at 30 per cent overload. Since the dielectric losses were calculated from the average power factor of about 100 feet of cable, it is possible that in localized spots much higher dielectric losses may develop, especially for some of the older cables.

Joints

As the result of high loading, asphaltum-base or petrolatum joint-filling compound may become so fluid as to migrate in large amounts into the cable insulation, thereby causing increased insulation losses; but this does not seem serious, especially since migration is usually limited to cable in the manhole which is subjected to lower temperatures. A further result is pressures or vacuums in the joints which may cause serious bulging or collapsing of the joint sleeves. Most lead joint sleeves, especially for the larger cables, have been too weak me-

chanically. For Chicago 13-kv 500,000-circular-mil joints, the new practice is to use only low-loss varnished cambric insulation as applied insulation instead of insulating tubes, and to use a circular sleeve of calcium-type lead alloy, $4^3/_4$ inches inside diameter and $^9/_{64}$ inch thick, instead of a $5^1/_2$-inch plain lead sleeve which was ridged to provide an air space at the top. So far, the practice is to continue using an asphaltum-base compound for filling.

SUMMARY

The outstanding effect of overloads up to 115 degrees centigrade upon multiple-conductor belted cables made since 1923 was an increase in ionization; but for only two old petrolatum cables was this effect serious enough to cause failure at 24 kv. At rated voltage the changes in ionization factor were small, and considerable recovery effect was noticeable during periods at moderate temperatures following overloads. It may, therefore, be expected that the effects of emergency loading to temperatures of 100–115 degrees will not be serious and that certainly limits of 90–100 degrees are conservative.

Power factors at normal operating temperatures should not be expected to increase much due to overloads, except for the cable adjacent to joints. In general, this effect should not be expected to shorten the life of the cable.

For copper temperatures up to at least 115 degrees centigrade, thermal instability is not a factor of danger, except for badly deteriorated or old rosin insulation.

Temperature Limits for Solid-Type 69-Kv Cable

The maximum permissible temperature for the insulation of single-conductor 69-kv cable has been based in Chicago largely on accelerated aging tests and a large accumulation of operating data. The joints in service are filled with a thin oil. Halperin and Betzer[8] showed that cables of good quality withstood for as long as seven weeks, without appreciable change, tests at $2^1/_2$ times normal operating voltage and daily temperature ranges of about 35 degrees to maximum copper temperatures of 65 degrees centigrade. Insulation thicknesses were $^{60}/_{64}$ to $^{69}/_{64}$ inch. Cables of the poorest qualities (made in 1926), which are now in service, showed considerable increase in power factor in a few days of such testing. However, these changes were not sufficient to cause failure at normal voltage, and such poor-quality cables constitute only a very small percentage of the 66-kv system.

Emergency ratings for the 66-kv lines in Chicago have for a few years been based on temperatures of 60–65 degrees centigrade, depending on the quality of the cable insulation, and on a maximum allowable daily range in temperature of 18 degrees. This limiting range is necessary for the insulation of cable now in service because (*a*) deterioration of the insulation occurs almost entirely by ionization in voids produced during cooling, and (*b*) the life of the cable may be shortened by radial expansion of the sheath as discussed later. For the year 1937, the maximum temperatures were 45, 50, and 55 degrees centigrade or less for, respectively, 75, 90, and 96 per cent of the lengths; and the very maximum was about 62 degrees.

Temperature Limits for the Insulation of Oil-Filled Cables

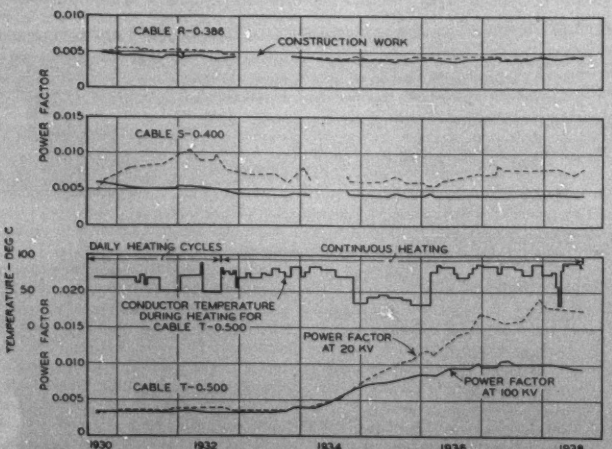
An experimental installation of oil-filled cable in underground conduit in Chicago, to which brief reference[10] has been made, consists of 1,000 feet of each of three kinds of cable made by two manufacturer's and designated as *R*-0.386, *S*-0.400, and *T*-0.500. The number is the nominal insulation thickness in inches. The cables are subjected to overvoltages, that is, to 76 kv to sheath, and to surges by means of a tap from an adjacent 132-kv three-phase overhead line. Heating current is supplied by current transformers insulated for 132 kv. Provision is made for measurements of power factor and average conductor temperature. The standard insulation thicknesses for 132-kv operation were 0.719 and 0.506 inch, respectively, in 1930 and 1938.

Testing was started in June 1930. Except for interruptions for various reasons, the cable was subjected to only voltage for one month, then to voltage with superimposed daily load cycles for two years, and subsequently to voltage and continuous heating to limit effects of daily movement on the sheath. As indicated in table VI, tests have been up to average temperatures of 91 degrees centigrade and to a maximum for short portions of the cable of 120 or 130 degrees. At interyals of two to three weeks, testing has been interrupted to allow measurements at both elevated and duct temperatures of power factors at various voltages from 20 to 100 kv.

Figure 4 shows the variations in power factor throughout the tests for each of the three cables, all power factors being adjusted to a conductor temperature of 60 degrees, through data from frequent measurements over a range in temperature. Figure 5 shows the maximum and minimum changes found in power factor-temperature characteristics among these cables.

Cable *R*-0.386 has remained entirely stable throughout the test. Cable *S*-0.400, also, has been relatively stable except for a moderate increase in the power factor at 20 kv early in the test. In general, this cable has undergone

Figure 4. Power factor of experimental oil-filled cable at 60 degrees centigrade



somewhat less severe heating than cable *R*-0.386, but the 33 days of heating to conductor temperatures of 90–91 degrees had no apparent effect on the power factor.

Cable *T*-0.500 remained stable during the first three years of testing and then developed instability, as evidenced by increasing power factors. A comparison of the temperature data and power factors for this cable indicates, however, that there is no consistent relation between the increases in power factor and the testing temperature. The 365 days of heating to 85–91 degrees had no tendency to accelerate the deterioration in electrical properties since the power factors at both 20 and 100 kv showed indications of approaching a stable condition during this period.

Increases in power factor of the same peculiar type, but of much greater magnitude than those which occurred on

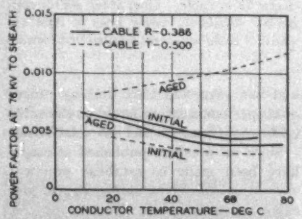


Figure 5. Change in power factor of oil-filled cable in eight years of experimental operation

cable *T*-0.500, were found also in one case on a portion of a commercial 132-kv line which had been subjected to only moderate temperatures. This showed that high operating temperatures are not essential for the occurrence of deterioration of this type and gave additional support to the conclusion reached above that the high temperatures to which cable *T*-0.500 was subjected were not in the main responsible for the instability found. In general, however, serious deterioration in oil-filled cable has been rare.

Figure 5 shows that such deterioration not only raises the power factor but changes the power factor-temperature characteristic from a relatively flat or falling curve to one which rises with increasing temperature. For cable *T*-0.500 the deterioration which has occurred is only a small fraction of that which would be necessary to cause failure due to cumulative heating. The increase in power factor which has occurred is, however, sufficient to reduce the carrying capacity by several per cent.

The results of these data and consideration of the earlier data in the paper and the references lead to the following conclusions:

(*a*). Changes in dielectric losses in oil-filled cable with time are not materially affected by increase in operating temperature, at least up to 90 degrees. This conclusion is not, as might be inferred, at variance with published data which indicate that the rate of deterioration in transformer insulation about doubles for each eight-degree-centigrade rise in temperature nor with the finding that rate of oxidation of oil exposed to air increases with temperature. The important deterioration in transformer insulation occurs in mechanical strength rather than in electrical properties and is caused by oxidation of the solid insulating material. The deterioration in oil-filled cable, which is usually negligible, is caused mainly by chemical changes in the oil which is in contact with only the materials sealed with it in the cable. Chemical changes of the oil do not necessarily result directly in increases in dielectric losses of the insulation.

(*b*). Oil-filled cable insulation may safely be operated continuously at copper temperatures up to 85 degrees and during emergencies at 90 degrees centigrade or more. These values are 5 to 15 degrees or more above the corresponding limits in the present Association of Edison Illuminating Companies cable specifications, where the limits already have been increased twice in the past five years.

Part II. Limitations Due to the Sheath

Radial Expansion of Sheath

As the temperature increases with load, the thermal expansion of the compound in insulation of solid-type cable causes an increase in the internal pressure and may result in serious sheath expansion. The rate of sheath expansion increases with increasing internal pressure and increasing temperature. Such matters and the properties of lead and lead alloys are covered in a recent research bulletin[11] on lead sheaths by H. F. Moore and others.

As far as load ratings are concerned, there seems to be no problem involving radial expansion of the sheath for low-voltage cable. The percentage of the volume inside the sheath that is occupied by compound is relatively small; and, because of the low electrical stresses in the insulation, void or gaseous spaces are not particularly objectionable. For cable that operates at about 12 kv and is connected with joints filled with a hard or plastic compound, the internal pressures at loads corresponding to emergency ratings may be 50 or 100 pounds per square

Table VI. Tests of Experimental 132-Kv Oil-Filled Cable in Chicago From Start to July 8, 1938

Cable	*R*-0.386	*S*-0.400	*T*-0.500
Total elapsed time (days)	2,934	2,934	2,934
Days of voltage application (76 kv to ground)	2,105.1	2,222.5	2,457.8
Number of daily load cycles to:			
Less than 65 deg C	197	99	216
65 to 74.9 deg C	364	462	345
75 to 79.9 deg C	0	1*	0
80 to 84.9 deg C	0	0	0
85 to 89.9 deg C	1*	0	1*
Total	562	562	562
Days of continuous heating to:			
Less than 65 deg C	49.8	265.0	216.9
65 to 74.9 deg C	592.8	371.2	464.7
75 to 79.9 deg C	590.5	222.6	308.2
80 to 84.9 deg C	142.4	19.6	235.3
85 to 89.9 deg C	48.7	0	336.8
90 to 91 deg C	27.8	32.9	27.8
Total	1,452.0	911.3	1,589.7

* During this cycle the heating current was applied continuously for nine days instead of the normal time of 12 hours.

NOTE: Copper temperatures are average values determined by resistance measurements. A recent longitudinal survey of duct temperatures revealed extremely large variations in temperatures—a condition never before even approached in Chicago except where steam mains were present. This conduit was installed for test purposes in a prairie and the condition and thickness of the soil covering varies greatly. It is estimated that for an average copper temperature of 90 degrees centigrade the maximum at one localized region was 120–130 degrees.

inch, as shown in the accelerated aging tests. Several cycles of emergency loading during the life of such cable may produce sheath expansion of 10 to 30 mils, but such expansion is small compared to the expansion that has been found on 69-kv single-conductor cable in Chicago which has operated successfully to date. It, therefore, seems that no trouble due to sheath expansion will occur on moderate-voltage cable.

If 69-kv solid-type cable with oil-filled joints is loaded rather heavily soon after installation, the internal pressure rises until the sheath is stretched enough to accommodate the heat-expanded insulation; and the pressures may be 50 or 75 pounds per square inch or more. Under usual loading conditions common daily maximum pressures are one-third or one-half of these values. As the sheath expands, oil enters the cable from the joints. For the 280 miles of such cable in Chicago that has been in service up to 12 years, the rate of expansion of the cable with $^{5}/_{64}$-inch sheath is about six mils in diameter per year, and this rate does not appear to be decreasing. For a relatively small amount of the cable in which $^{5}/_{64}$-inch sheath was used, the rate of sheath expansion has been roughly twice as much.

In the first few years of service, open-

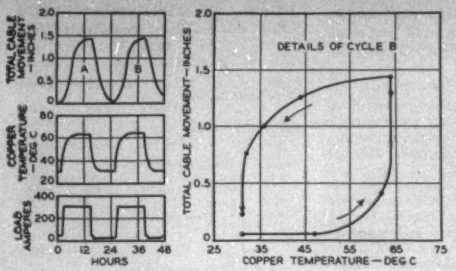


Figure 6. Cable movement for line with block-type loading

For 391-foot length of 350,000-circular-mil three-conductor 13-kv cable

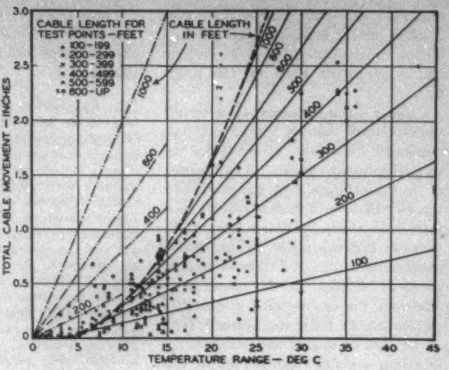


Figure 7. Theoretical and actual cable movement

Data are for 500,000-circular-mil three-conductor 13-kv cable. Lines at left are for copper-bar expansion, while lines at right are values of cable movement derived from formula

ings developed mainly at defects in the sheath structure. With further service, openings developed at the thinnest portion of sheaths that varied considerably in thickness around the circumference. In most of these cases the minimum thickness of the sheath initially was less than 85 per cent of the average thickness. Sheaths produced prior to 1930 developed high rates of trouble when the average expansion around the circumference exceeded about three per cent. More-recently-made sheaths are better in quality and in concentricity and should withstand internal pressures much better.

Accelerated aging tests[9] have shown that as far as the insulation is concerned the daily temperature range for the 69-kv cable could be increased from the present limit of 18 degrees centigrade to 30 or 35 degrees. Such an increase is not feasible for solid-type cable with thick insulation and connected with oil-filled joints unless a sheath with increased creep resistance is provided.

Induced Sheath Potentials on Single-Conductor Cable

For single-conductor cable installed with insulating sleeves and bonded to eliminate sheath losses, the induced sheath potentials vary directly with the magnitude of the alternating current and directly with the distance between insulating sleeves. In 1929 it was suggested in an AIEE paper[13] that, on the basis of laboratory and field experience, the limiting a-c potential between sheath and ground should be 12 volts in order to avoid a-c electrolysis. The general idea then was that this limit would apply during the time of the maximum expected load.

Since then, in order to provide further field data on the effects of the a-c potentials in causing electrolytic sheath corrosion, fireproofing has been removed periodically in many manholes from cable that has been submerged. No corrosion was found except in one case where the sheath also had a slight positive d-c potential on it inadvertently. These cables in general had operated with a-c potentials up to about ten volts. In view of these and other data, it was decided in 1935 that the maximum safe induced sheath potentials to ground for the usual daily loading should be 11 volts and that during emergencies the potential could go to 15 or 16 volts. When the loadings cause higher potentials than these values with cross or auxiliary cable bonding,[12] it is necessary to use sheath-bonding transformers to make the sheath potential to ground one-half of the induced sheath potential in the length of cable between insulating sleeves. Even with bonding transformers and ordinary spacing of the ducts, the usual and maximum loadings may be limited to approximately 875 and 1,250 amperes, respectively, in case the sections of cable are about 600 feet long.

Cable Movement

It has been accepted usually that in the determination of the load rating of a cable the allowable copper temperature should be based solely on characteristics of the insulation, although there has been some discussion of the possibility that the life of the sheath should also be considered. The noticeable number of sheath cracks found especially in cable which has been installed for ten years or more has served to put added emphasis on consideration of the life of the sheath and has suggested that limiting ranges of copper temperature based on allowable cable movement should be established.

Since no previous published attempts have been made to establish practical working relationships among sheath life, cable movement, and load ratings, it has been necessary to start at the beginning and see what could be learned (*a*) about the relation between cable movement and loading and (*b*) about the relation between cable movement and sheath life. Operating and laboratory data bearing on these points have been collected and studied for over 12 years in Chicago. The results of these studies have provided a basis for quantitative discussion of both phases of the problem.

Cable Movement as a Function of Load Range

It has generally been assumed that cable movement should be directly proportional to temperature change and to cable length, allowing for a constant percentage of reduction of movement due to flexing or snaking of the cable in the ducts. Field data, however, have failed to corroborate this assumption. This was thought to be due to the masking influence of the many indeterminate disturbing factors which are present in actual underground systems. It now appears that by taking into account the *restraining forces* due to friction in the duct and to the training of the cable in the manholes, the field data on cable

movement become intelligible. A review of the theory will be given.

Consider a length of cable in a duct in which neither tension nor compression is present. Evidently a reduction in the temperature of the cable, which tends to cause it to contract, must develop enough tension to "pull" the length of cable between the manhole and any given point before there can be any movement at that point. The maximum possible tension which could be developed is that required to move the cable along the entire length from the manhole to the center of a duct run. The effect of a temperature reduction cannot be manifested entirely as contraction of the cable, since some of it appears as tension.

Assume now that the maximum tension which can be developed by load cycles and friction in a duct run is present when heating starts. Part of the thermal expansion relieves tension. Part of it tends to push the cable out of the duct mouth, but this takes force, which can be developed only by compresssion of the cable and must be great enough to "push" the portion of cable which actually moves. As heating progresses, the remaining tension becomes localized nearer and nearer the center of the length, while the cable near the ends becomes compressed and produces movement. Finally, maximum compression is developed, it being that force which is just sufficient to push all the cable from the center toward either end. The actual movement appearing at the duct mouth is that portion of the expansion remaining after the tension and compression requirements are fulfilled.

These points are illustrated in figure 6, which gives movement data obtained on a certain well-loaded 12-kv three-conductor line, which had unusually abrupt changes in load. During the first portion of the load cycle, the increase in copper temperature does not result in any appreciable movement at the duct mouths. Instead, the cable becomes compressed. As the temperature increases, the forces developed finally exceed the force required to push the cable through the duct, and movement takes place at the duct mouths. On the cooling cycle, considerable drop in copper temperature occurs before the cable commences to move back into the duct. The copper temperature must decrease enough to relieve the existing compression in the cable, and then must build up sufficient tension to overcome the frictional forces tending to prevent the retraction of the cable.

Figure 8. Cable-movement indicator

Top—Indicator installed to measure cable movement at a duct mouth. The range in movement over a period of time is obtained by measuring the separation of the two riders shown on the rod which butts against the duct wall

Bottom—Indicator installed on a cable joint to determine the limits of the lateral movement of the joint to and from the manhole wall

In the equations for cable movement, the following symbols are used:

M = total movement in inches for a length of cable
L = length of duct in inches
C = coefficient of thermal expansion of cable (16.7×10^{-6} approximately)
A = cross-sectional area of copper in circular inches
W = weight of cable in pounds per inch
D = coefficient of friction for cable in the duct
E = Young's modulus of elasticity for cable in pounds per circular inch ($15 \times 10^6 \times \pi/4$ approximately)
k = maximum longitudinal stress which may exist in the cable at the duct mouth, due to the restraining force of the cable in the manhole
T = copper temperature change in degrees centigrade
$T_c = (WDL + 2k)/AEC$, the temperature change necessary to produce the maximum possible change in stress throughout the cable

If a condition of maximum *compression* were present at the start of a heating cycle, the total movement would be the same as for the thermal expansion of a copper bar, that is,

$$M = LTC \text{ inches} \qquad (1)$$

Under actual conditions of normal cyclic movement, the state of maximum compression or of no initial strain would never be present at the start of a heating cycle. Either part or all of the cable would be under maximum tension. For this condition, which is characteristic of uniform cyclic loading, the cable movement is given by the following formula:

$$M = AEC^2(T - 2k/AEC)^2/2WD \text{ inches} \qquad (2)$$

This formula is to be used up to the point where $T = T_c$. At higher temperatures the formula to be used is

$$M = LC(T - T_c/2 - k/AEC) \qquad (3)$$

Equation 3 takes account of the temperature rise being more than sufficient to overcome the effects of tension, compression, and the restraining force k in the manhole. Neither equation 2 nor 3 takes account of flexing. The cable is considered to act as an elastic column. Numerical values for use in these equations are readily available except for the variables C, k, and D.

The coefficient of thermal expansion of cable might differ somewhat from the coefficient of expansion of a copper bar. The coefficient C for cable would therefore include, for example, the effect of buckling strands or restraint due to the sheath. No definite evidence that buckling occurs has ever been found in Chicago. The sheath does not appear to offer much restraint. The temperature change of the sheath is less than for the conductor, but this is almost exactly offset under stable conditions by the greater coefficient of thermal expansion for the lead sheath. The lag of the sheath temperature behind the copper temperature in normal load cycles may have some slight effect, but calculations confirmed by one laboratory test show that C for cable in ducts that are not submerged is about the same as for copper, that is, $C = 16.7 \times 10^{-6}$ approximately.

The restraining influence k of the cable in the manholes is variable and data on it are scanty. For typical horizontal and vertical offsets of the joint with respect to the duct mouth, the force is estimated from one full-scale laboratory test to be roughly 300 pounds for a three-conductor 500,000-circular-mil 13-kv cable. It is assumed that the force of 300 pounds is built up at some part of the heating cycle to oppose the expansion of the cable into the manhole; then, as the cable cools down, the force drops to zero and builds up to 300 pounds in the opposite direction. An installation of cable having small offsets in the manhole would require a greater force to cause

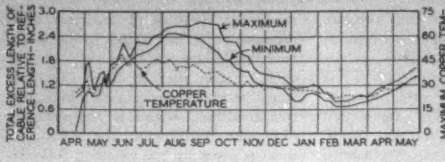

TOTAL EXCESS LENGTH OF MANHOLE JOINT — INCHES
MAXIMUM COPPER TEMPERATURE — DEG C
MAXIMUM
MINIMUM
COPPER TEMPERATURE
APR MAY JUN JUL AUG SEP OCT NOV DEC JAN FEB MAR APR MAY

Figure 9. Weekly data for cable movement over one year

For 506-foot length of 69-kv 2,100,000-circular-mil single-conductor solid-type cable

bending than one with large offsets, and the movement would be correspondingly less. The flexibility of the fireproofing used on the cable in the manhole has a marked influence.

The coefficient of friction of cable during installation may vary greatly with different cable and duct materials, but a fair average value, based on many measurements of pulling strains during the past 12 years, is 0.5. This value has been used for D, and is probably accurate enough for any length of cable being pulled or pushed in a duct by cable movement, except where a long length is being pushed. In the latter case, it would be necessary also to include the effect of flexing in a duct and the resultant component of pressure against the sides of the duct. This has not been included, as no values for such conditions were available. The friction coefficient under service conditions may be somewhat reduced where there is vibration of the conduit.

Figure 7 shows curves from equations 1 and 3 for one type of cable. Field data are shown for comparison. The straight lines emanating from the origin are for the theoretical expansion of copper bar, which is given by equation 1. The parabolic fan of lines to the right is obtained from equation 3. The dashed line is the calculated movement that would occur on an *infinite* length of cable; for example, regardless of length the total movement at the two ends could never exceed 1.7 inches for a temperature range of 20 degrees centigrade. This is not due to flexing, since equation 3 is not set up to take account of it. It is due solely to the fact that a large percentage of the thermal expansion is taken up by longitudinal compression or tension in the cable.

If flexing were taken into account, the calculated movement would be even smaller. It might be still further reduced by the occurrence of enough flexing to make the cable anchor itself firmly in the duct at widely-separated points, thereby reducing the effective cable length. Although these phenomena are known to occur, the theory is conservative in not taking them into account.

The movement follows the dashed line as long as compression is building up in the cable. When the maximum possible compression for the length under consideration has been reached, the movement thereafter becomes directly proportional to temperature rise and diverges along a straight line. The point of divergence occurs at large temperature rises for the longer lengths, for example, 14 degrees for a 600-foot length. This means that no matter how long a length of cable may be installed, its movement will be no greater than that of a 600-foot length, as long as the temperature range does not exceed 14 degrees. After the point of divergence is passed, longer lengths move more than short ones; but the 1,000-foot length in figure 7, for example, moves only 46 per cent more than the 500-foot length for a temperature range of 25 degrees.

The difference between one type of cable and another is negligible as long as the ratio of conductor cross section to total cable weight is similar. The calculated movement for 69-kv 2,100,000-circular-mil single-conductor cable and 5-kv 375,000-circular-mil three-conductor cable is about the same as for the 13-kv cable in figure 7. It is much less for heavy cables with small conductors, such as 132-kv 600,000-circular-mil single-conductor cable with 719 mils of insulation.

The conclusions derived from the theory are strongly supported by the field data obtained on various cables at more than 250 locations during the past 15 years. Usually the movement has been measured in adjacent manholes at the two ends of the length. In some cases the lateral movement of the joint has been obtained also. Data have been gathered at each location for periods ranging from one day to one year. The instruments used for obtaining complete records such as shown in figure 6 are graphic recorders. Where only the limits of the movement are desired, the indicator shown in figure 8 is used. Since this is more convenient to install and maintain than the recording devices a large number have been put into use.

A continuous record of cable movement for a year is shown in figure 9 for a length of 69-kv single-conductor cable. The record illustrates that movement has two components, the daily movement due to load cycles and the annual movement due to changes in ground temperature. The two solid lines form the envelope of the daily oscillations which are superimposed on the seasonal cycle. Both the seasonal and daily movements are fairly well distributed between the two ends of the cable. Field data obtained in many cases indicate that the probable distribution of movement between the ends of a length is 60 and 40 per cent, although a 50-per-cent distribution is not uncommon, and, in a few cases for small movements, the entire movement of a length will appear at one end. The assumption used in Chicago is a 60- and 40-per-cent division of the total movement.

The annual movement is usually larger than the daily, but obviously only the daily movement is of importance in causing sheath cracks. The annual movement may have some indirect effect such as changing the training conditions in the manhole or forcing the joint against the wall. In Chicago the seasonal range in ground temperature is about 18 degrees

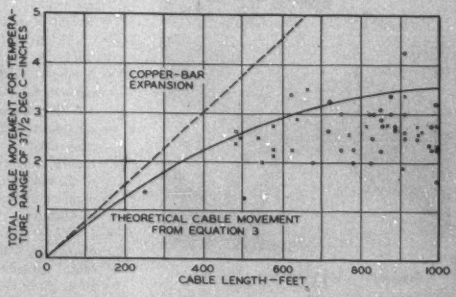

TOTAL CABLE MOVEMENT FOR TEMPERATURE RANGE OF 31½ DEG C—INCHES
COPPER-BAR EXPANSION
THEORETICAL CABLE MOVEMENT FROM EQUATION 3
CABLE LENGTH—FEET

Figure 10. Cable movement on a 69-kv line of the Cincinnati Gas and Electric Company

⊙—Slope of conduit three per cent or less

×—Slope of three to six per cent

centigrade. The usual daily range in copper temperature for 500,000-circular-mil three-conductor 13-kv cables has been about 8 degrees centigrade although it has on rare occasions reached 35 or 45 degrees.

Figure 7 shows that actual daily cable movement is usually less than indicated by equation 3, particularly for the higher temperature ranges. Some test points in the lower temperature ranges are higher than the calculated values, but this is partly due to errors in estimating the temperatures as indicated elsewhere in the paper; the cable movements involved, moreover, are small and relatively unimportant. The few recorded cable movements for the higher ranges that lie above the lines given by equation 3 are probably for cables installed under different conditions than were assumed—that is, less friction in the duct, smaller restraining forces in the manholes, a different initial state of tension or compression, or a combination of these factors. To illustrate, data designated by T for 69-kv 2,100,000-circular-mil single-conductor cable have been inserted in figure 7. These points are all for 600-foot lengths of cable which were installed in winter and left without load until the middle of summer. Thus they were subjected to sufficient seasonal rise in ground temperature to approach maximum compression. Upon application of the first load cycle they would tend to obey equation 1; that is, the movements should be about the same as the theoretical expansion of bar copper, and so they were. Subsequent daily movements have been normal, that is, much lower.

The daily movement is less, in general, than calculated for all the many types of cables installed in Chicago, as illustrated for the 13-kv cable in figure 7. This means it is safe to accept the calculated values as an upper limit of daily movement. It strongly indicates also that flexing or anchoring of the cable in the duct often occurs. Undoubtedly other factors, such as abnormally high values of duct friction and restraint in manholes, help to decrease the movement in some cases, but certainly not in all cases. For some of the very low values plotted for the 400- and 500-foot lengths, the field records show that practically no movement occurred at one end of the length, which definitely indicates flexing and anchoring. Another such indication is the wide spread in recorded values of movement for any one length and temperature range; for example, for 300–400 feet and 18 degrees the movements range from 0.2 inch to 1.06 inch. Any assumptions that now appear reasonable concerning variations in duct friction and manhole restraint can account for only part of this spread.

It is concluded that there is no objection, from the standpoint of cable movement, to the installation of cable lengths that are much longer than have usually been considered practicable in the past.

Some installations of long single lengths of cable in normal underground ducts have been made in Cincinnati. The cable is 500,000-circular-mil, single-conductor, 69-kv, oil-filled with 315 mils insulation and $^9/_{64}$-inch lead sheath. Cable movement data, for which the author is indebted to the Cincinnati Gas and Electric Company, are shown in figure 10, along with the theoretical movement calculated from equation 3. The cable movement was entirely in accordance with what would be expected from the previous discussions herein; for example, the movement for 900–1,000-foot lengths is only slightly greater than for 500-foot lengths, and the movement is generally much less than for 13-kv 500,000-circular-mil three-conductor cable in which the ratio of copper cross-section to cable weight is relatively much greater. These data are of interest also because some of the conduit sloped considerably, while Chicago conduits are almost always horizontal. There was a tendency for the cable movement at the downhill end of a sloping length to exceed the movement at the uphill end, but no permanent downhill migration was found. This is in accordance with the theory which indicates that downhill creep would occur only for shorter cable lengths or larger temperature ranges than prevail in Cincinnati.

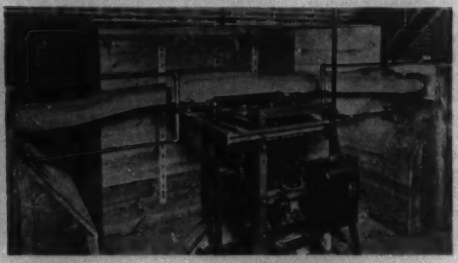


Figure 11. Dummy manhole apparatus

Figure 12. Sheath cracks developed in the dummy manhole tests

Top—Cracks on straight cable near the duct mouth

Bottom—Cracks adjacent to the joint wipe

Sheath Life

During 1920–24, the importance of sheath cracks on the Chicago underground system was coming to be fully appreciated, partly because the number of sheath repairs and line failures due to cracks was too high. In 1925, inspectors examined as many of the 24,000 manholes as was feasible, with the result that 500 or 600 sheath cracks were found. Many of the manholes were found to be too small from the standpoint of cable movement, and the protection at duct mouths and supports was found to be inadequate to prevent wearing of the sheath. A program for remedying these deficiencies was instituted and has since been vigorously followed, with the result that two-thirds of the present manholes conform to present standards. The present standards for straight-type manhole sizes are 8 feet by $4^1/_2$ feet for manholes

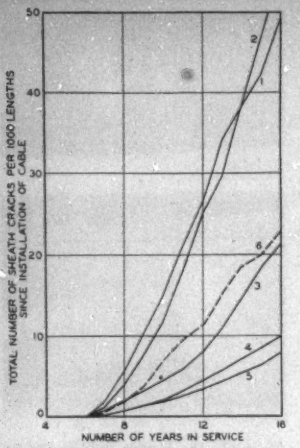


Figure 13. Sheath cracks on 500,000-circular-mil three-conductor 13-kv cable

1—Lengths 400–500 feet
2—Lengths 300–400 feet
3—Lengths 200–300 feet
4—Lengths 100–200 feet
5—Lengths 0–100 feet
6—Total rate for all lengths

to contain three-conductor 5-kv cable with conductor sizes of 375,000 circular mils or less, 10 feet by 6 feet for three-conductor 500,000- or 650,000-circular-mil 13-kv cable, 11½ feet by 6 feet for 750,000- or 1,000,000-circular-mil solid-type 69-kv cable, and 13 feet by 6½ feet for 2,100,000-circular-mill solid-type and oil-filled-type 69-kv cable. The minimum headroom is 6 feet in all cases.

As a result of the rehabilitation program, the number of sheath cracks found per year has been cut approximately in half. About 86 per cent of the sheath cracks on the transmission system are found and repaired before they develop into electrical failures. The methods of repair have evolved and improved somewhat with time. At best, however, operating experience has demonstrated that many of the repairs are satisfactory for only a limited time.

Laboratory studies carried on along with the rehabilitation program have consisted mainly of tests made in the full-sized "dummy" manhole illustrated in figure 11. The manhole is of the standard octagonal shape used in Chicago, with the ducts at the middle of the end walls. The length is adjustable. In a test, a 20- to 25-foot length of cable is used. The training, jointing, and fireproofing are varied to suit the test, but are done in accordance with field procedure. A motor-driven device imparts the desired amount of reciprocating motion to the cable at both duct mouths in order to simulate cable movement. The duration of a test cycle is either 70 or 110 seconds. Three-hundred-twelve cycles are taken as the equivalent of one year of life. In order to indicate sheath failure, oil pressure is supplied to the joint. The appearance of oil or cable compound shows a sheath crack. Figure 12 illustrates the appearance of the cracks. They are similar to cracks developed in sheaths in service and their division among joint wipes, duct mouths, and bends is about the same.

Sixty-seven tests have been made and more are planned. Many of the test results are not directly applicable to problems in the present study. However, they confirm, in general, the proposition that sheath life is greater for longer manholes and for greater offsets between axes of joints and cable at the duct, but the data are not sufficient to determine numerical relationships. Some calculations, however, indicate that an increase in offset is two or three times as effective, within limits, in prolonging sheath life as an equal increase in length of bends. This benefit of increased offsets is based on no accompanying increase in concentration of bending at the duct mouth and joint wipe. Tests indicate that sheath life is shortened by concentration of bending as occurs in service. Studies are being made of schemes to prolong the sheath life in small manholes that cannot be enlarged.

Some definite figures on the life of various sheaths under certain conditions have been obtained. The findings for two types of sheaths on 13-kv and 69-kv cables installed in "standard" sized manholes are summarized in table VII. The average life of commercially pure sheath of 13-kv three-conductor 500,000-circular-mil cable is about 20 years, when installed in a manhole ten feet long from duct to duct, with an offset of 19 inches (18 inches horizontal, 6 inches vertical), with a cable movement of 0.75 inch at each duct mouth and with the joint free to move on the supporting bracket.

The duty on the sheaths of cable in actual service has been considerably less severe than in the tests as far as cable movement is concerned, but more severe with respect to manhole conditions, especially for lines which were installed in manholes built 12 or more years ago. Different lines have, of course, been subjected to different conditions, especially as to loading.

Table VII. Life of Sheaths in Dummy Manhole Tests

Kind of sheath	Commercially pure lead	Calcium-type lead alloys
Kind of cable	500,000-circular-mil, three-conductor, 13-kv	
Number of tests	9	2
Sheath life in years:		
Minimum	9.6	31.6
Average	20.8	38.3
Maximum	34.5	45.0
Kind of cable	750,000-circular-mil, single-conductor, 69-kv	
Number of tests	4	5
Sheath life in years:		
Minimum	9.6	38.2
Average	18.5	67.8+
Maximum	23.8	80.0+

NOTE: Movement at each duct mouth was about 0.75 inch. The sheathing of cable with calcium-type alloys was done on an experimental basis.

The effect of differences in loading is seen in the fact that 45 per cent of the cracks that occurred in 500,000-circular-mil three-conductor cable operating at 12 kv during the five-year period 1933–37 were confined to the 13 per cent of the lines which carried the heaviest loads. Obviously, some lines must carry relatively heavy loads. These lines had normal cable movement for daily temperature ranges of about 15 degrees centigrade during the 11-year period 1927–37, whereas the average range for the remaining 87 per cent of the 12-kv lines in the same period was only 7 degrees, with correspondingly less movement. The effect of small manholes and of inadequate protection at duct mouths and supports

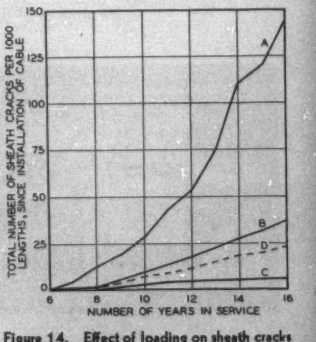


Figure 14. Effect of loading on sheath cracks in 500,000-circular-mil three-conductor 13-kv cable

Average Loading of Lines During 1927–1937 (Amperes)

Curve	Range	Mean
A	250–315	277
B	200–249	225
C	Up to 200	175
D	All lines	205

was to shorten the life of the cable. In spite of the rehabilitation program, the effects of previous conditions are still being felt. For example, in 21 out of 29 typical cases of sheath cracks occurring in 1937, there were prominent contributing factors such as small manholes, wearing at old duct mouth before manhole was enlarged and adequate protection provided, and abnormalities in sheaths such as solder patches applied for bond-wire connections or repairs of former cracks. All of the 29 cables involved were 10 to 15 years old.

Similar findings in varying degrees apply also to the cables operating in Chicago at 120 to 33,000 volts, appreciable percentages of which were installed before protection and training had been improved. They do not apply to the 66-kv and 132-kv cables, which were all satisfactorily protected against wearing and were installed largely in manholes that still appear to be of sufficient size for the usual daily temperature ranges of 5 to 15 degrees centigrade that have prevailed. The measured daily cable movement has been about 0.1 to 0.5 inch at each duct mouth, with an average of about 0.25 inch. Assuming that the sheath life is inversely proportional to the amount of daily movement, then, according to table VII, an average sheath life of about 50 years would be expected, with a possible minimum of about 25 years. It is still too soon to tell what the actual sheath life will be, although a few cracks have occurred, most of them at bond wipes or where the sheath was damaged. The oldest lines have been in service 12 years.

The life of 13-kv cable sheaths has been studied to determine the influence of the age, loading, and length of the cable, with the results shown in figures 13 and 14. About 7 or 8 years after installation a few lengths developed sheath cracks. After 15 years of service the number of cracks has been about two per cent of the number of lengths, some lengths having more than one crack. The longer lengths developed about twice as many cracks as the short lengths, but lengths over 400 feet did not have many more cracks than those between 300 and 400 feet. This is to be expected from the relative amounts of cable movement. Also, the lengths over 400 feet are often part of installations in exceptionally favorable locations. For example, such lengths are common on 12-kv lines installed along with 66-kv lines, for which especially long manholes are provided.

The rate of cracking was much higher on the lines that had higher average loads. Figure 14 shows that the group of lines having the highest average weekday loads (277 amperes) developed about 130 cracks per 1,000 lengths after 15 years of service compared to 30 cracks per 1,000 lengths for moderately-loaded lines (225 amperes average) and 5.6 cracks per 1,000 lengths for lightly-loaded lines (175 amperes average). In this study the load for each line was treated as follows:

(*a*). The maximum three-hour average load for each week in the year was taken from the records; and the average of these 52 values was called the yearly average.

(*b*). The yearly average was determined for each of the 11 years in the period 1927–37, inclusive.

(*c*). The over-all average of the 11 yearly averages was used for the average load on each line.

The individual lines were grouped in accordance with their average loads, as indicated in figure 14, which shows the mean for each group and also the grand average for all lines.

One very important application of the findings on cable movement and sheath life is the determination of the effect of increased loading. For example, the loading on the 13-kv cables in Chicago is

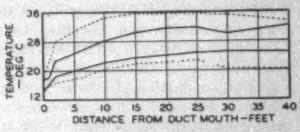


Figure 15. Temperature gradients of empty ducts at typical locations

being increased to provide greater transmission efficiency. An increase over the past 11-year loading of about 18 per cent in the average load is expected for the 87 per cent of the lines that carry the lighter loads. The increase for the remaining lines, which carry the heavier loads, will probably be held to about 8 per cent to limit sheath cracking. The probable effect on the life of the cable sheaths over a period of years is indicated in table VIII.

The increased rate of sheath cracking, excluding the effects of increasing age, would boost the total rate of cable failures from 3.2 to about 3.8 failures per 100 miles per year, assuming that the present efficiency of locating and repairing sheath cracks will be maintained and no substantial changes in manhole conditions take place. The increase does not appear alarming at first, but it is to be expected that most of the additional failures will appear on the more heavily loaded lines and result in a high rate for those lines. There are reasons for supposing that the life of sheath would decrease somewhat faster than the cable movement increases. There would be a considerable increase, also, in the time and expense of repairing sheath cracks. On some of the heavily-loaded lines, cable replacements might be necessitated because of excessive cracking in certain manholes.

The present study is limited to about 15 years because of scanty data on older cables. For this reason, any figure for the total sheath cracks on older cables could be obtained only by extrapolation on figure 14, with possible error. The number of sheath cracks on the oldest cables having the heaviest loads is probably higher than normal now due to lingering effects of former manhole conditions. These effects will gradually disappear as the cables with damaged

Table VIII. Effect of Increased Loads on Sheath Life of 500,000-Circular-Mil Three-Conductor Cable Operating at 12 Kv

	Average of Lighter-Loaded Lines (87 Per Cent of Total)		Average of Heavier-Loaded Lines	
	Former Conditions	Future Conditions	Former Conditions	Future Conditions
Average of weekday maximum loads (amperes)	195	230	277	300
Daily range in copper temperature (deg C)	7	10	15	18
Average cable movement at a duct mouth in inches:				
0–200-foot lengths	0.025	0.045	0.07	0.09
200–300-foot lengths	0.05	0.11	0.204	0.26
300–400-foot lengths	0.06	0.16	0.312	0.40
400–500-foot lengths	0.06	0.19	0.400	0.52
over 500-foot lengths	0.06	0.19	0.456	0.625
Approximate number of sheath cracks in per cent of lengths in 15 years:				
In 200–300-foot lengths	1.0	2.6	9.2	14
In 400-foot and longer lengths	1.4	6.8	45*	65*
In all lengths	1.3	5.4	13.0	19

* Based on relatively meager data.

sheaths are weeded out, but an upward trend in sheath cracks and service failures with increased loading and age will remain.

The magnitude of movement which is producing sheath cracks is 0.6 inch and less at each duct mouth for almost all of the cases involved. This movement is less than might have been expected to cause such cracks and less than that which gave an average sheath life of 20 years in dummy manhole tests.

One way of obtaining increased loading efficiency without seriously reducing the sheath life would be to make the manholes still longer and wider, notwithstanding the small amount of movement involved. This has the obvious disadvantages of requiring great time and expense and of not being always feasible owing to lack of space in the streets. Another method is to try to improve other conditions affecting movement and cracking, but the prospects are not too bright for such a solution. A better method is to obtain more resistant sheath.

The results of the dummy manhole tests (see table VII) show definitely that the life of calcium-type lead alloy sheaths, which were furnished on an experimental basis, is at least twice as great as for commercially pure lead. Such alloy sheaths have outstanding resistance also to radial creep and to abrasion, making for an ideal combination of qualities. Lead containing two per cent tin was no more resistant to bending in a few tests than commercially pure lead, and antimony alloy was less resistant.

It seems that for many cables the expected time of present-day commercial sheaths to cracking in manholes is only one-third to two-thirds of the life of the insulation, at least for Chicago. Apparently better sheath materials are needed to resist the effects of cable movement. Then a *balanced* cable design will become available, but it would be many years before the full advantage of installing such cable could be realized on an underground system.

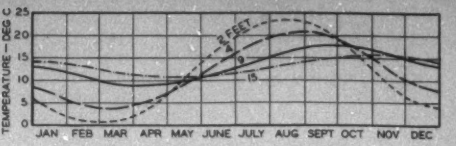


Figure 17. Seasonal variation in ground temperature at various depths

Curve for four feet is used as general ambient

Part III. Heating Characteristics of Conduits

Some work on determining temperatures of conduits has been done in Chicago since 1910. From 1923 on, however, such work has been unusual in that it has been on a *continuous* basis for the entire city and has been supplemented with many special investigations. The resultant data have afforded a continuous basis for determining the allowable loading of cables and the allowable number of cables to put into a given conduit, without the necessity for large factors of safety to take care of unusual or unforeseen variations in the heating characteristics and without danger of the conduit temperatures and resultant cable temperatures materially exceeding the maximum values expected from survey data and calculations. This eliminates such fears as were expressed in a 1921 AIEE meeting[13] that "The operating man does not know where the hottest spot in his system is, and from the operating man's point of view, as I see it, I should prefer to keep the rating down to a reasonably conservative basis."

An inquiry just made by the author concerning the practice of 18 utilities indicates that most of them (having over 65 per cent of the cable in the country) closely follow the temperatures of conduits and cables where the temperatures are the highest, and 15 of them make some routine conduit temperature measurements.

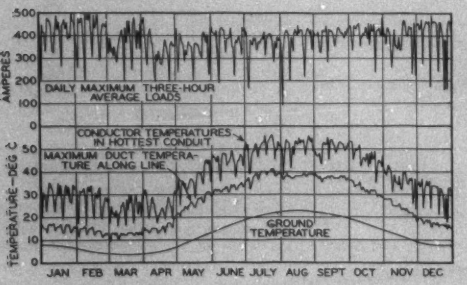


Figure 16. Load and temperature records for a 69-kv 750,000-circular-mil single-conductor solid-type cable

Annual Temperature Surveys of System

In connection with operating the system or with proposed additions to it, the Commonwealth Edison Company makes routine and special surveys of conduit temperatures every year, thereby measuring 2,500 to 6,000 spot temperatures. These surveys yield considerable information also on water conditions. Most of these data are obtained in the summer, which is almost always the time of highest cable temperatures, even though the loads may be heavier in the winter.

The duct temperatures are obtained with mercury thermometers attached to a steel tape and inserted 20–25 feet into the apparently hottest empty duct. As illustrated in figure 15, the results of numerous detailed surveys of temperatures between manholes have indicated that temperatures taken 20 feet from the duct mouth are not influenced by manhole air. This is contrary to the opinion that temperatures taken 5 or 8 feet from the duct mouth are satisfactory and to another statement that 25 feet[14] is not far enough.

To obtain air temperatures in a duct containing cable, it is necessary that the cable fireproofing be broken away at the duct mouth and then later replaced. In addition, it appears difficult to get consistent results on the air temperature with a temperature-indicating device inserted between the cable and the duct, where the clearance is often only one-half inch.

The gas-filled bulbs of about 36 recording thermometers are installed approximately 25 feet into the hottest duct in the hottest location found in the annual surveys for each important line and installed also at other special locations. At any other location along the route of the line, the temperature may be estimated at any time during the year on the basis of records from these thermometers along with temperatures and other data obtained in the annual survey.

A record is kept for each location having a recording thermometer as indicated in figure 16. Another Chicago practice is

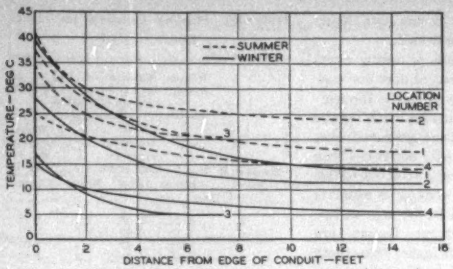


Figure 18. Temperature gradient laterally from conduits

to determine and record for each week the maximum load and the maximum three-hour average load for each line operating at nine kilovolts and over. Periodic load checks are made for lower-voltage cable.

Recording thermometers are installed at various depths in the soil at two locations remote from all other sources of heat for the purpose of establishing ambient earth temperatures. As indicated in figure 17, the annual variation in ground temperature becomes less with depth. The heating characteristics of a conduit section are based on the temperature rise of the air in that conduit above the ambient earth temperature corresponding to its depth.

Special Surveys

When large irregularities in the heating conditions along a section of conduit are indicated or suspected—such as an external source of heat being close to a portion of the conduit—then longitudinal temperature surveys are made. A 410-foot cable with thermocouples attached at 20-foot spacings is used. After this cable is installed in a selected empty duct, it may be moved to permit temperature readings at any desired spacing.

Usually the duct-temperature rise varies less than 10 per cent along the conduit section, except for the end 15 feet or so. Where one conduit crosses another, the temperature rise has been found to be as much as five or ten degrees centigrade in excess of normal. Another example of a special case occurred where a leaking steam main crossing the conduit created an excess temperature rise of about 50 degrees.

In 1926, thermocouples were installed in a plane at right angles through the conduit at ten different kinds of locations. At each location 20 thermocouples were placed in the periphery of the conduit and in the soil for 2 feet on each side of the top and bottom and for 15 feet each way from the sides. The principal findings are illustrated in the typical curves in figure 18. This study, together with other field observations, indicates that from 70 to 85 per cent of the total temperature drop from the hottest empty duct to the base earth temperature occurs from the side of the conduit and through soil, provided the width of the conduit is four ducts or less. Furthermore, separations, even though small, of adjacent conduits are found helpful. To make the heat effect of one conduit on an adjacent conduit negligible, the separation between conduits should be about twice the combined height of the two conduits, although separations over 15 feet are probably unnecessary. A slight advantage in heat conductivity was indicated for conduits using precast concrete ducts as compared to fiber ducts.

In 1936, thermocouples were installed transversely through a variety of conduits at four different locations mainly to aid in determining what value of thermal emissivity should be used for the sheaths in connection with calculating the rise of the sheath above empty-duct temperatures. Typical cross sections are shown in figure 19.

Although it had been appreciated that the temperature rises through conduits varied considerably with circumstances, the results obtained, as illustrated in figure 20, were surprising. If the empty-duct temperature is used as the ambient, then even for the cable in the hottest ducts it appears conservative, especially for the heavier loads, to employ the usual sheath emissivity constant of 1,200 degrees centigrade per watt per square centimeter. With reference to the air surrounding a cable in a duct, the sheath emissivity constant is usually 550 or less. These statements are based on the fact that for losses of four watts or more per foot of cable, most of the sheath temperature rises were below the lines drawn on figure 20 to correspond to the sheath emissivity constants of 1,200 and 550, respectively. Chicago data, together with other data, indicated also that the rise in temperature between the air in the occupied duct and the air in the hottest adjacent empty duct may be roughly, one degree centigrade per watt per foot of cable. Kirke[14] has indicated that the unit temperature rise of the sheath decreases as the cable losses (and sheath temperature) increase, and it appears that this phenomenon might well be taken into account for, particularly, very high loads, although it has not usually been done in Chicago.

The above tests showed that, contrary to the findings of some authors,[15,16] not all the heat comes to the ground surface during each season of the year. Usually in the summer the top row of ducts is hotter than the bottom row. The test results confirm the previous finding that the corner ducts are cooler by a small margin over other outside ducts.

Other Results of Surveys

Heating characteristics of conduits have been found to vary with the following conditions, excluding the effects of whatever neighboring structures may be present: type of soil, moisture content of soil, season of the year, size and material of duct, number and configuration of ducts, depth of conduit, and number of cables installed.[17,18] Considerable information has been published on the first two items. In Chicago, the temperature rise of the conduits in the soil having the poorest heat-dissipating characteristics is five times the rise in the best soil, all other conditions being the same, and

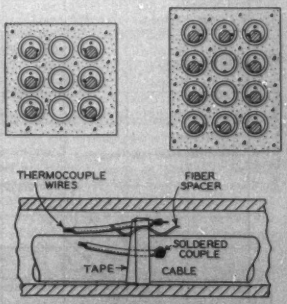


Figure 19. Installation of thermocouples in underground conduits

Thermocouples were placed in air or attached to sheath as indicated, and leads were imbedded in concrete of conduit and soil up to special terminals near street surface

excluding conduit under water. For the soils usually encountered, this ratio is 1.4 to 1. The conduit and soil dissipate the heat less readily in the summer than in the winter, the variation being from 1.3 to 1.

An increase in duct size increases the perimeter of the conduit and, thereby, decreases the unit thermal drop to base earth. Increasing the depth of the conduit may bring the conduit in contact with wetter soil,[19] but unless water is reached this is counterbalanced by increased length of the path of the heat flow to the ground surface.

As illustrated in figure 21, the duct temperature during any 24-hour period almost always varies only a few degrees, or less, and this variation is generally less than 15 per cent of the temperature rise of the duct above ambient earth, even though the cables have daily load factors of only 50 or 60 per cent. In view of such data, the conduit heating constants for determining the temperature rise for the hottest empty duct are calculated on the basis of the *average* heat loss during the 24-hour period. The maximum duct temperature usually occurs two hours after the maximum heat load.

Except for week ends or during emergencies, the heat generated does not vary considerably from day to day. In emergencies, correction must be made for the effect of the excess heat generated over the usual amount of heat; and it has been found that the temperature rise due to this excess reaches 40 per cent of its ultimate value in one day and 60 per cent in two days. These attainment factors are much lower and much higher than those given by some other investigators.

Instability of the heating constant has been found where the soil around the conduit was unusually dry and perhaps full of sizable voids, and where the duct temperature was somewhat above 50 degrees centigrade. An example of what

Figure 20. Temperature rise of sheaths above air in four conduits

All rises have been corrected to cable with 2^7/$_8$-inch diameter when diameter was different. One type of point in graph for each location

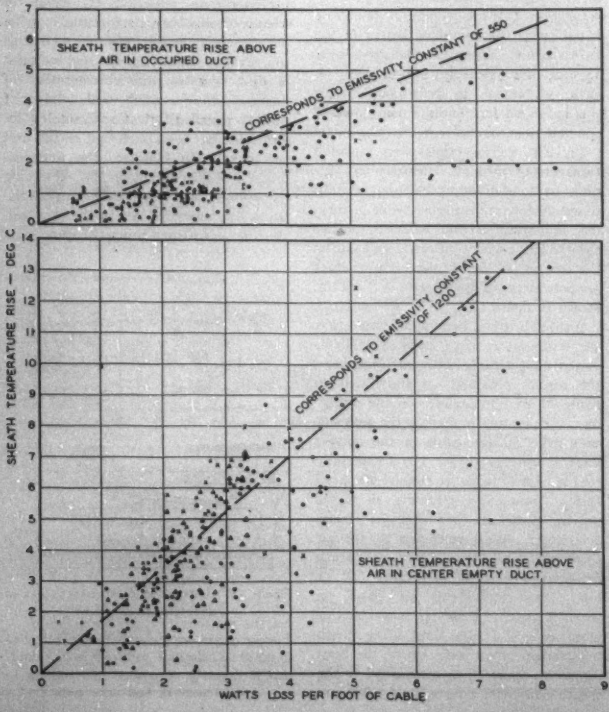

SHEATH TEMPERATURE RISE ABOVE AIR IN OCCUPIED DUCT
CORRESPONDS TO EMISSIVITY CONSTANT OF 550
CORRESPONDS TO EMISSIVITY CONSTANT OF 1200
SHEATH TEMPERATURE RISE ABOVE AIR IN CENTER EMPTY DUCT
SHEATH TEMPERATURE RISE — DEG C
WATTS LOSS PER FOOT OF CABLE

Table IX. Heating Constants for Underground Conduits

Number of Ducts	Heating Constant in Deg C per Average Watt of Loss Over 24 Hours per Foot of Conduit: Summer (June 1–October 31) Chicago	NELA[11]	Kirke[14]	Winter (November 1–May 31) Chicago
4	1.42	0.93	1.5	1.26
6	1.17	0.82	1.2	1.04
8	1.02	0.77	1.0	0.91
9	0.98	0.77	1.0	0.87
12	0.89	0.74	0.86	0.79
16	0.79	0.72	0.75	0.70
20	0.72		0.67	0.64
24	0.64		0.60	0.57

NOTE: Above is based on only the outside ducts being occupied with cables carrying load.

may occur in such rare circumstances when the heating load in the conduit increases substantially above its usual value is illustrated in figure 22. In a few days the heating constant increased from 1.8 to 2.9 degrees centigrade per watt per foot of conduit. Even in this case the daily range was not more than 20 per cent of the duct-temperature rise.

In January 1921 a rare record of heating load of conduit and duct temperature was obtained on a short length of heavily-loaded conduit adjacent to a d-c substation. The conduit had 30 ducts containing 25 cables. The load on these cables was heavy for eight hours of each day, and light the remainder of the time. The maximum duct temperatures for the first five weekdays were, respectively, 80, 89, 94, 94, and 96 degrees centigrade with a daily variation of 20–25 degrees. The soil was a little better than average from a thermal standpoint. Since all cables involved were operating at 115 volts direct current, no cumulative cable heating resulted.

From studies of the two experiences cited, as well as considerations of soil characteristics in general, it appears that the maximum allowable duct temperature, if serious drying out of poor soil is to be avoided, is about 50 degrees centigrade. This limit agrees with Church's general recommendation.[20] For fair or average soil, this limit might be increased about 10 degrees; and for compact soil containing over 15 per cent moisture still further increases seem justifiable, although they are unlikely to be useful.

For a given conduit containing a given number of cables, the temperature surveys have indicated that the heating constant for a given time of year may vary considerably from the average in previous years. This is one outstanding

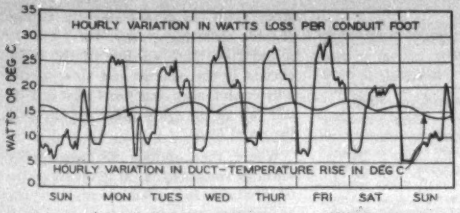


Figure 21. Heat and temperature variations in a conduit

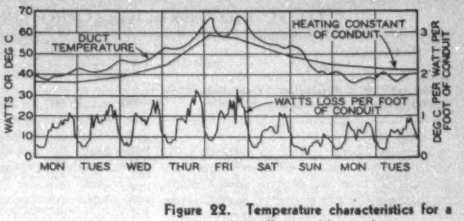


Figure 22. Temperature characteristics for a thermally unstable conduit

reason for making temperature surveys year after year. Detailed studies for 298 locations in Chicago showed variations ranging from 0 to about 50 per cent, the average being 20 per cent. The variations in percentage were less for the poor but fairly stable soils.

Heating constants for fair conditions with only outside ducts occupied are given in table IX. In Chicago, many center ducts are occupied by small cables used for relaying, signals, and voltage indications.

When data from temperature surveys and cable loads indicate that changes should be made in order to avoid excessive temperatures, the procedures successfully used are illustrated by the following:

1. When the problem requires an immediate solution, the conduit is usually flooded.

2. The soil around the conduit, especially when the heating characteristics are poor, may be replaced with bank-run sand and gravel. In such cases the replacement is for the soil from the surface to a depth in line with the bottom of the conduit and extending for about two feet on each side of the conduit. In one case, for instance, the result of this replacement for a 16-duct conduit was to reduce the heating constant from a range of 1.65–2.23 to 1.05–1.32. Since this conduit contained 12 single-conductor 13-kv cables which together served one side of a large transformer, it was not feasible to remove any of the cables. Even where it is feasible to remove cables, it has been found more economical in some cases to replace the soil instead.

3. One or more cables may be removed from the conduit.

4. The existing cable may be replaced with cable having a larger conductor.

5. A ventilated manhole may be installed where one conduit or a steam main crosses another conduit.

6. A steam main crossing a conduit may be specially insulated, and the separation perhaps increased.

In general, 9- or 12-duct conduits are the most economical in Chicago from an over-all standpoint, except where space is limited, in which case a greater number of ducts must be used. On the other hand, if it is known that the total number of cables will not exceed, say, four, then a 4-duct conduit should be built. On the Chicago system about 17 per cent of the total length of all ducts is in conduits having more than 12 ducts. The present trend in construction will reduce this percentage.

Table X. Maximum Allowable Temperatures for Some Chicago Cables

Kind of Cable			Maximum Copper Temperature Used (Deg C)	
Operating Voltage (Kilovolts)	Number of Conductors	Type	For Normal Rating	For Emergency Rating
0.12	Any	Solid	85	105
4	Any	Solid	85	105
9	3	Old rosin	81	95
9	3	Solid	81	95
12	3	Old rosin	77	90
12	1	Solid	80	100
12	3	Solid	77	90
66	1	Solid	58 or 60	60 or 65
132	1	Oil-filled	70	80

NOTES: Three-conductor cable is of belted type; same cable of a given design is used for 9 and 12 kv. Temperatures for normal ratings are in accord with present rules. Above limits are used for the 132-kv cable already in service, because they give ample ratings for system requirements.

Part IV. Principles and Methods of Calculation

The method of calculating the ratings is in line with literature prepared by Simmons[21] and others. The chief principles and assumptions follow:

(*a*). Thermal resistivity of the insulation, the value of which is based mainly on Chicago tests, is taken as 550 degrees centigrade per watt per cubic centimeter for oil-filled cable, 600 for solid-type 69-kv cable, 650 for modern solid-type 5- to 35-kv cable, 800 for lower-voltage cable, and 900 for old rosin-impregnated cable.

(*b*). The thermal emissivity of the sheath is assumed to represent the thermal drop from the sheath to the air in the hottest unoccupied duct, and based partly on some test data is taken as 1,200 degrees centigrade per watt per square centimeter for cable with a diameter of three inches or more. For smaller cable the constant used is smaller, for example, 1,165 and 1,005 for two- and one-inch cables, respectively. For three cables in a duct, the equivalent surface is taken as 2.25 times the surface of one of the cables, while for two cables it is taken as 1.83 times the surface of one cable.

(*c*). In calculations of a-c resistance of cable, corrections are made for skin effect, copper proximity effect, and sheath losses. Skin effect is determined from Ewan's curves.[22] The copper proximity for multiple-conductor cable is usually assumed to be one-half the skin effect except for "compack" conductors, where it is considered as zero. The sheath losses in the three-conductor cable are calculated on the basis of Meyerhoff's[23] formula. For segmental single-conductor cable, the magnitude of the skin effect is assumed to be the same as for a conductor having a d-c resistance equal to 2.6 times the resistance of the conductor under consideration.

(*d*). The dielectric losses are determined from test data. For each type of cable a conservatively high dielectric loss-temperature curve is used. In determining the temperature rise of the conductor above sheath, it is assumed that the entire dielectric loss passes through one-half of the insulation resistance for single-conductor cable and through two-thirds of the insulation resistance for three-conductor cable.

(*e*). The cable dimensions are approximated for the cable as furnished. For instance, the sheath thickness is taken as being five per cent more than the nominal thickness, and the insulation thicknesses for 13-kv cable are taken as being six per cent more than the nominal thicknesses.

(*f*). In the calculation of general ratings, the heating constant is based on fair soil and on normal depth of conduit. In the determination of load ratings for special cases, investigation is made of conduit and ground conditions pertaining to each case to determine the specific heating constant applicable.

(*g*). Ground temperatures are taken as practically the highest that will occur during the two periods of the year, that is, 14 and 23 degrees centigrade for winter and summer, respectively, for conduits at normal depths.

(*h*). For general ratings, the first calculation, which is important, is based on the most prevalent size and on conservatively large conduit sections.

Table XI. Load Ratings for Typical Cables in Chicago

Cable			Rating in Amperes			
			Normal		Emergency	
Normal Size (Circular Mils)	Number of Conductors	Operating Kilovolts	Summer	Winter	Summer	Winter
1,500,000	1	0.12	1,230	1,330	1,460	1,520
375,000	3	4	340	375	400	425
250,000	3	9	230	255	260	285
500,000	3	12	365	410	420	463
350,000	3	33	315	375	340	400
750,000	1	66	460	480	510	550
1,100,000	1	132	450	550	735	825

NOTES: Ratings are for the maximum three-hour average load during a day. Single-conductor cable has no sheath losses. The normal ratings for the example of 132-kv cable are limited by thermal conditions created by other cable in the same conduit.

(*i*). The characteristics of the loading of the cable as to daily load factor, heating load factor (ratio of average loss during 24 hours to loss corresponding to average load over the three-hour maximum period), and ratio of usual daily maximum three-hour average load to normal rating are based on present and expected future trend. This three-hour average load is usually five or eight per cent below the very maximum load during a day and gives a good practical value to use in determining temperature rise of a cable. The heating load factor is usually taken, for instance, as 60 per cent for 13-kv three-conductor cable and as 70 per cent for 69-kv single-conductor cable; and the ratio of daily maximum three-hour average load to normal rating is taken as 68 and 90 per cent for the two cables, respectively. An example of an exception is for nine single-conductor cables feeding the 12-kv side of a large transformer; then the calculations are based on all nine cables having maximum loads equal to the normal or emergency ratings.

(*j*). The maximum allowable copper temperatures used at present in Chicago, as indicated in table X, are, in general, less than recognized as safe in part I of this paper. It is considered wise to be conservative on this matter until additional test data and, more particularly, operating experience are available, especially because of the probability of an excessive number of sheath cracks incidental to extra-high copper temperatures. In some instances, the ratings actually used produce lower maximum copper temperatures than given in table X, because of any of the following limitations: (1) allowable maximum duct temperature, depending on the type of soil; (2) allowable maximum duct temperature, depending on other installed cable that may be predominating in importance over the cable under calculation; (3) allowable daily range in temperature for heavy solid-type insulation.

(*k*). The cable movement at the duct mouth is determined mainly from the standpoint of the usual expected daily maximum load. The accepted maximum allowable movement for the usual daily loading is 0.5–0.75 inch at a duct mouth, the lower maximum applying for the more important cable. The cable movement is given a little consideration in connection with the emergency rating.

Ratings are usually determined for two periods of the year, summer and winter. For the important 66-kv tie-lines where the desired loading is frequently great and the load may be controlled, it has been found advantageous to give a special set of ratings applying for the periods of June 1–July 15 and October 1–31 in order that during these periods the ratings may be above the midsummer ratings. For each period of the year, calculations are made for all kinds of cable for the normal ratings and for the emergency ratings. The emergencies are considered to last one and two days, respectively, for solid-type and oil-filled cable because experience shows that repairs may be made to a circuit within those periods. In addition, special ratings are occasionally calculated where requests are made for larger than the general ratings and it is found that the lines are installed under abnormally favorable conditions, or where the surveys of the group following temperatures show the ratings should be less than the general ratings on account of subnormal local thermal conditions. Another special set of ratings is given for some tie-lines where the emergency will exist for only one or two hours, with the result that the temperature rise of the cable and conduit during the emergency is materially less than would be the case for protracted operation. The transient heating characteristics of the cable in such cases are determined on the basis of data by Miller and Wollaston.[24]

The common size outside the downtown area in Chicago is the 500,000-circular-mil three-conductor 13-kv cable operating at 12 kv. It is assumed in the first calculation that there are eight such cables in a 12-duct conduit, and the normal ratings are determined on the basis that seven of the cables have a usual daily maximum load of 68 per cent of the normal rating and that the eighth cable is carrying the rated load. The emergency ratings are then calculated on the basis that seven of the cables are carrying the calculated usual load and the eighth cable is carrying the emergency load. In determining the ratings of cable operating at, say, 4 kv, it is assumed that there are five of the 12-kv circuits in the conduit and three of the 4-kv cables, and that the 12-kv circuits and two of the 4-kv cables are carrying the usual loads.

Where the conduits are abnormally warm or congested, as at generating stations, where 12- or 16-duct conduits may be less than ten feet apart or may cross in some cases, it is the practice to specify an extra-large size of conductor in order that the portion of circuits in such conduits shall not limit the carrying capacity of the circuits as a whole. For example 650,000-circular-mil is used in place of the usual 500,000-circular-mil conductor on the three-conductor lines operating at 12 kv; and 1,000,000-circular-mil is used in place of the 750,000-circular-mil conductor on the single-conductor lines operating at 66 kv. The use of the extra copper for a short part of a line has been found to be an extremely economical procedure.

The general ratings are given for some typical cable sizes in table XI.

References

1. DEFINITIONS AND GENERAL STANDARDS FOR WIRES AND CABLES, AIEE Standard No. 30.

2. Report of cable research at Massachusetts Institute of Technology under the direction of Professor V. Bush. NELA *Proceedings*, volume 84, 1927, pages 1451–7.

3. DETERIORATION OF IMPREGNATED CABLE PAPER SUBJECTED TO TEMPERATURE ONLY, AIEE JOURNAL, volume 44, May 1925, pages 508–10.

4. RATE OF DETERIORATION OF IMPREGNATED WOOD-PULP CABLE PAPER SUBJECTED TO HEAT ONLY, NELA *Proceedings*, volume 86, 1929, pages 1493–1504.

5. THE EFFECT OF HEAT ON PAPER INSULATION, H. W. Fisher and R. W. Atkinson. AIEE TRANSACTIONS, volume 40, 1921, pages 143–64.

6. PYROCHEMICAL BEHAVIOR OF CELLULOSE INSULATION, F. M. Clark. AIEE TRANSACTIONS, volume 54, 1935, pages 1088–94.

7. LOADING TRANSFORMERS BY COPPER TEMPERATURE, H. V. Putman and W. M. Dann. AIEE TRANSACTIONS, volume 58, 1939, pages 504–14.

8. PERMISSIBLE OPERATING TEMPERATURES OF IMPREGNATED PAPER INSULATION IN WHICH DIELECTRIC STRESS IS LOW, Philip Torchio. AIEE TRANSACTIONS, volume 40, 1921, pages 107–29.

9. STUDIES OF STABILITY OF CABLE INSULATION, Herman Halperin and C. E. Betzer. AIEE TRANSACTIONS, volume 55, 1936, pages 1074–82.

10. NEW OIL-FILLED CABLE LINES IN CHICAGO, Herman Halperin and G. B. Shanklin. AIEE TRANSACTIONS, volume 56, 1937, pages 739–48.

11. AN INVESTIGATION OF CREEP AND FRACTURE OF LEAD AND LEAD ALLOYS FOR CABLE SHEATHING, H. F. Moore, B. B. Betty, and C. W. Dollins, with a chapter on EXPANSION OF SHEATHS ON UNDERGROUND POWER CABLES IN SERVICE, Herman Halperin. Bulletin No. 306, Engineering Experiment Station, University of Illinois, 1938.

12. REDUCTION OF SHEATH LOSSES IN SINGLE-CONDUCTOR CABLE, Herman Halperin and K. W. Miller. AIEE TRANSACTIONS, volume 48, April 1929, pages 399–414.

13. AIEE TRANSACTIONS, volume 40, 1921, pages 183–4.

14. The Calculation of Cable Temperatures in Subway Ducts, Wallace Kirke. AIEE Journal, October 1930, pages 855-9.

15. Cable Heating in Underground Ducts, Ressel D. Levy. *General Electric Review*, April 1930, pages 230-40.

16. Current Rating of Cables for Transmission and Distribution, S. Whitehead and E. E. Hutchings. IEE *Journal*, October 1938.

17. Operating Temperature of Underground Cables, C. A. Bauer. 1930-31 Report of Engineering Section, Great Lakes Division, NELA, pages 239-51.

18. Earth Temperatures and Their Use in Rating Cables, NELA No. 021, December 1929.

19. Permissible Current Loading of Cables Buried 20 Feet Below the Surface, E. B. Wedmore and E. Fawssett. Report 137, BE and AIRA, Paris, June 1933.

20. The Economic Loading of Underground Cables, Elwood A. Church. AIEE Transactions, volume 54, 1935, pages 1166-72.

21. Calculations of Electrical Problems of Underground Cables, D. M. Simmons. *The Electric Journal*, May to November, inclusive, 1932.

22. A Set of Curves for Skin Effect in Isolated Tubular Conductors, A. W. Ewan. *General Electric Review*, volume 33, number 4, pages 249-51.

23. Discussion, R. W. Atkinson. AIEE Transactions, volume 50, 1931, page 998.

24. Thermal Transients and Oil Demands in Cables, K. W. Miller and F. O. Wellaston. AIEE Transactions, volume 52, March 1933, pages 98-113.

Discussion

G. B. Shanklin: See discussion, page 560.

Wm. A. Del Mar: See discussion, page 561.

L. I. Komives (nonmember; The Detroit Edison Company, Detroit, Mich.): Mr. Halperin's findings were very interesting in regard to the beneficial effect of increased offsets in manholes versus manhole lengths. What other means have been found in Chicago to prolong the life of the lead sheath by changing conditions in the manhole outside of lengthening it or broadening it?

Under the heading "Summary," in part I of the paper, a remark is made as follows: In general, this effect (power factor increased at normal operating temperatures) should not be expected to shorten the life of the cable adjacent to joints. It seems that in the experience of The Detroit Edison Company the presence of joint-filling compounds of petroleum base, because they mix readily with the cable impregnating compounds, results in a considerably higher power factor.

E. W. Davis (Simplex Wire and Cable Company, Cambridge, Mass.): Careful field records and research data are of infinite value to the cable manufacturer. No product made is first presented in its perfect state even for services in which conditions are static; and for utility distribution systems which continually change in practice, economics, and operating conditions, it is even more evident that continual change and improvement is essential in its component parts. Such work as here presented which sums up manufacturers' results and technique, field experience, and economic distribution practice definitely points the way to further work by manufacturers to develop more satisfactory cable for present day practices.

The conclusions drawn by the author are general. With a problem containing so many variables probably no general conclusion is safely applicable to all cases and bears out the contention of cable engineers which is of many years standing that current ratings by manufacturers must be approximate and then considerably on the safe side.

Undoubtedly some increase in operating temperature could be allowed based on the probable performance of modern cable insulation only. However, such increase is counteracted by detrimental features concerned mainly with the performance of the lead sheaths such as expansion from pressures, cracking, electrolysis, and also probable changes in heating constants of the ducts and surroundings due to drying out. It is interesting to note that in the main all detrimental features are due to varying conditions imposed by load cycles.

More definite practices and rules governing permissible overloads have been greatly needed for many years. Here again it is probably not practical to use a general rule but allowable overload temperatures and their durations could well be developed for various insulations. The present AIEE rule for maximum continuous operating temperature is not complete enough for modern uses. The author's tests and summation approaches this subject.

The question of thermal stability of old rosin cables is interesting. We know of very old rosin-rosin oil cables of high loss still operating at 12 kv after many years. Thermal stability at this voltage is not appreciably affected by losses in spite of the great agitation on this subject a few years ago.

The opinion given that admixing of joint compound with cable compound is not detrimental is interesting and also directly opposite to the ideas of some other utility engineers. We are inclined to agree with the present writers in this respect for moderate voltage cables.

Part II of the paper dealing with sheaths is quite unique and well done, particularly that part dealing with equations for expansion of cable. We would not expect the coefficient of a cable to be as near to that for a solid copper bar as here taken. The lay of cabling and stranding must have some effect. Considering a stranded single-conductor cable in which the strands are laid at an angle of 30 degrees, an increase in the length of the strand is not directly applied to the length of the cable as shown below:

Let

l = lay or pitch of strand along cable
d = pitch diameter of layer
L = length of strand
$= \sqrt{l^2 + (\pi d)^2}$

Let L increase by ΔL and assume no change in pitch diameter

$$L + \Delta L = \sqrt{(l + \Delta l)^2 + (\pi d)^2}$$

or $l = L \cos 30°$

It would be expected that

$$\Delta l - \Delta L \times \cos 30° = 0.866\,\Delta L$$

and that

$$C \text{ effective} = 16.7 \times 10^{-6} \times 0.866$$
$$= 14.5 \times 10^{-6} \text{ for the assumed case}$$

This effective coefficient would be different for multiconductor cable and different again where tension or pressure existed since there is no reason why either could not change the angle at which the longitudinal force of expansion and contraction is acting.

With reference to sheath life we find the probable life as determined by test very interesting. Many improvements in lead-sheath quality and workmanship have been made quite recently and undoubtedly more will follow. Thicker lead sheaths promise some help but alloyed sheaths may give equal or better results more economically.

Robert J. Wiseman (The Okonite-Callender Cable Company, Passaic, N. J.): Mr. Halperin has written a very remarkable paper, describing the researches his company has been conducting for many years and now have reached a point where the story may be told. I think the title might be changed to something like "Why Cables Operate as They Do" for he gives a very fine exposition of the problems of operation and how they might be solved. He is helping all of us better to appreciate the utility's operating problem and we cable manufacturers will have to give considerable study to his paper and in fact all of the papers dealing with cable operation in order to find how we can help to improve their operation or increase their life. Therefore, our attention is brought to the statement in the third paragraph under Part I in which he states that the main consideration is the influence of heating on the ability of the cable to withstand removal and reinstallation without material lowering of the dielectric strength of the cable. I think that all of us will agree that if we could keep a cable at a constant temperature continuously we would be willing to agree to higher temperatures than are standard at the present time, but it is the upsetting effects of the high and low temperatures that the cable is subject to that causes a cable to lose its physical as well as electrical properties. Its life is shortened and, therefore, we must try to hold down the maximum temperature in order to get as far as we can guess a life expectancy that is in fair agreement with other kinds of equipment. As Mr. Halperin states, there is a scrapping of a cable before its useful life is reached because of causes other than insulation deterioration and one of these is that the cables have not been operated in most cases to their present permissible temperature. Until we do get this experience it is difficult for us to accept higher permissible temperatures than now set up. As this experience can only come from the utilities we must await their collecting the information for us.

This is equally true of the emergency rating of cables. We don't know how much a cable will lose in years of life by short periods of overloading. It has not been possible to determine it because the last 12

to 15 years have seen a remarkable improvement in the quality of oil and paper as well as manufacturing methods. If the MIT research were conducted today it is possible that we would find less deterioration than in 1926 when it was made. If it were possible to follow closely the daily load cycle on a cable and its history for several days previously, a method for determining an emergency rating could be set up that would still keep the maximum conductor temperature close to the permissible values. It would be a tedious job and require almost continuous calculating of the conductor temperature as the load varied. It would not be practical. A comparison of transformers and cables in their emergency ratings is not entirely possible. The former has plenty of oil which can circulate and assist in cooling and also a large volume of material for heat absorption and if moved, it is done as a unit without upsetting the insulation. For cables we have small volume, no oil circulation to assist cooling, and the cables during their expected life will be moved. The aging of transformers due to heating has been well studied from the life expectancy viewpoint and, therefore, the limits set up are probably based on this knowledge. Why should cables be set as high as transformers in the light of the difference in their make-up and operation?

Mr. Halperin's description of his aging tests on 12-kv cable with pressure-tight potheads and open potheads checks our experiences on aging tests on 69-kv solid-type cable. When we sealed up the end of the cable and conductor to prevent oil flow from the pothead into the cable we obtained higher pressures and higher vacuum in the cable than when the ends were left free to permit the flow of oil back and forth and obtained a longer life on cables with ends open. We then studied the effect of more freedom of flow of oil between a joint and a cable by eliminating the varnished cambric wrapping and substituting tubes and open-mesh cotton tapes directly over the connector. We got better stability, lower pressures, and longer life. We have suggested to several utility engineers that better operation would be obtained if this were done and I hope some will do so soon. This will eliminate the experience described by Mr. Halperin on joints in part I. I cannot appreciate how using low-loss varnished cambric taping is going to improve the mechanical problems of his joints.

Part II dealing with limitations due to the sheath is very instructive. Mr. Halperin's experience that increasing the lead thickness $^{3}/_{64}$ inch cuts the expansion in half is what we found years ago and I have reported it at other meetings. We found this to be true when comparing $^{6}/_{64}$ inch to $^{9}/_{64}$ inch, and $^{9}/_{64}$ inch to $^{12}/_{64}$ inch. It is one of the reasons that I advocated years ago increasing the wall thickness of our large-diameter cables in order to reduce the radial expansion. I still believe in it.

For single-conductor cables the oval-shaped conductor with a circular sheath is the solution of the internal-pressure problem. This has been proved in tests by our associate company in England, The Callender's Cable and Construction Company, and in our laboratories. On new cable we did not exceed an internal pressure at the sheath of 20 pounds per square inch and a vacuum higher than 5 inches, whereas on circular conductors we have gotten 85 pounds per square inch pressure and 20 inches vacuum. We have obtained about 25 per cent longer life on accelerated aging tests using oval conductors. An oval conductor and free-flowing joint will give a much longer life in single-conductor solid cables than obtainable with round conductors and solid joints.

I wish to congratulate Mr. Halperin on the section dealing with the manner in which a cable moves with changes in temperature. It is understandable and sounds logical and makes us glad to know that cable movement is not as much as we thought and how fortunate we are. If it did move in the amount a solid copper rod expands, the utilities would be experiencing a greater number of lead failures and replacements which is costly, or would have to build much wider ducts which is also costly. I would like to ask one question. How much actual influence will the size of the cable compared to the size of the duct have? The restraining forces in the duct for a cable close to the size of duct will be higher than for a smaller cable in the same duct, but the chance of snaking or flexing in the duct is less in the former. Do they offset each other so that we can say that all cables act alike in the same duct?

We have been told by utility engineers of the cracking of lead sheaths near the duct mouth due to cable movement and have been studying ways of overcoming it. We have considered cutting the sheath and inserting a bellows which relieves the lead and permits cable movement at one location. One of the companies had the same idea.

Part III, dealing with the heating characteristics, brings forth few questions to discuss as it is well written and quite detailed. Under "Annual Temperature Surveys of System," fifth paragraph, reference is made to using the maximum three-hour average load in determining the load factor. Although this is usually done, we have wondered sometimes on what basis a three-hour time period has been taken instead of a one-hour period.

Under "Special Surveys," fifth paragraph, is not the low surface emissivity constant of 550 likely to be due to inaccuracy in measuring the air temperature, the latter probably being too high which would give a low temperature gradient? We consider temperature measurements in an empty duct more accurate. The temperature of the duct wall for a duct containing cable is probably not more than one or two degrees higher than the temperature in the empty duct due to heat conduction of the concrete.

Part IV, item *b*—we understand the thermal emissivity of a sheath is assumed to represent the thermal drop from the sheath to the air in the same duct and not to the air in the hottest unoccupied duct. The thermal duct constant takes care of the duct and the surrounding earth. We like the method proposed by Kirke, and which is used in England, to use a separate term for the duct structure and another for the earth. If this is done, the earth term can vary according to the kind of soil. We also hope that some day a study of these constants for a small number of ducts in a duct bank and very few cables installed will be determined experimentally so that we will be more sure of what they are than we are today.

E. R. Thomas (Consolidated Edison Company of New York, Inc., New York): Mr. Halperin is to be complimented on the scope and treatment of the various factors influencing the load ratings of cable. In part II the treatment of cable movement presents a fresh theoretical explanation of the magnitude of movement which will probably be encountered and the wealth of field test data seems to confirm the theory advanced.

In connection with induced sheath potentials on single-conductor cables treated in this section of the paper I would like to point out that Searing and Kirke in an article "Reduction of Sheath Losses in Single-Conductor Cable," *Electrical World*, October 6, 1928, suggested the desirability of limiting the voltage between cable sheaths to a value of 200 volts during fault conditions. This limit was set as one dictated by safety to personnel who might be working in manholes containing these cables during the period when a fault occurred. It was assumed that high-voltage circuits in general had impedances in the form of transformers or protective reactors which would limit the fault currents to approximately ten times the full-load currents and thus it was expected that the voltage between sheaths under normal load conditions would be about 20 volts and the voltage to ground about 12 volts. Tests were carried out on lead electrodes and short lengths of cable sheath and the data were reported showing the loss in weight which might be expected for various current densities of alternating current. From this data it was the conclusion that this arbitrary value of 20 volts between sheaths set up from safety considerations was a value of potential so low that the expected sheath life of cable due to a-c electrolysis would far exceed the expected life of the cable due to other causes even when that cable was installed and operated in the presence of high-conductivity tidewater.

We have not experienced any failures due to a-c electrolysis during the period of years which we have operated single-conductor cable installed with cross-bonds as described in the article by Searing and Kirke. Some of these cables normally operate at voltages to ground in excess of 15 volts and are submerged in tidewater. I do not feel that voltage values of even 20 volts to ground would be a factor detrimental to the life of the cable due to any a-c electrolysis which might result even if the cables were operated submerged in high-conductivity water. If one considers the possible shock hazard involved it would seem quite likely that considerably higher differences of potential may be experienced on a system using sheath-bonding transformers.

L. F. Roehmann (Hastings-on-Hudson, N. Y.): I want to comment on Mr. Halperin's paper, on the section dealing with the cable movement. The cable engineers should be thankful to Mr. Halperin and his collaborators that they considered, for the first time, the restraining and frictional forces in studying cable movement due to

temperature changes. The conditions are similar to those occurring in the rails of a railroad track which are also subjected to movement and to internal stress. In the cable technique these problems are, of course, of lesser importance than in railway engineering, but I am glad that they have been broached.

If one tries to check the formulas presented in Mr. Halperin's paper, one has some difficulties. Therefore I would appreciate it if Mr. Halperin would indicate, perhaps in an appendix, how and under which assumptions these formulas are derived, inasmuch as they form the base for the subsequent discussion of the experimental results.

Herman Halperin: The submitted discussion on this paper, as well as other discussions that have been given me, is greatly appreciated.

Some of the discussers apparently have missed one of the main points of the paper, which is that emergency ratings have become feasible, not because of mere conjecture, but because of a thorough engineering study which brought out the big increase in the quality of installed lines during the past 15 years, the moderate temperatures at which cables are usually operated, the indications of little or no deterioration in tests of various kinds of cable and of paper insulation by itself at temperatures much above those now allowed by the existing rules for cables, etc. Although it may have been wise 18 years ago (time of presentation of similar papers) to keep temperatures always below the limits given by the AIEE rules, it does not seem wise to do so now in view of the various large improvements since made by manufacturers and by utilities.

As is recognized in the paper, the use of the emergency ratings may result in moderate increases in maintenance and in failures, but even with these increases these items will be small as compared with what prevailed 15 years ago. The tendency for these items to increase will, of course, be counterbalanced by further improvements.

Another point that pertains particularly to the solid-type cables is the fact that emergency ratings based on temperatures greatly in excess of the temperatures permitted by existing rules are feasible provided the usual daily loading is moderate. If the daily loading is heavy, with the result that the cable operates at temperatures very close to the limits now allowed by the AIEE rules, and furthermore if the loading varies considerably during each 24 hours so as to result in large daily temperature ranges, then the margin of safety in the installed underground circuit is decreased. This means that the safe temperature for emergency operation becomes less than would be the case for moderate loading.

Wiseman points out that the operating companies have not collected much information on the operation of cable up to the present permissible temperatures. Of course, this is due to the fact that the permissible temperatures were applied to the rare emergency conditions, which resulted in building cable systems to operate normally at very low temperatures. In order to operate the cables nearer to the present permissible temperatures, it is necessary to permit the temperatures to exceed these limits during rare emergencies.

Apparently some discussers have not taken full cognizance of the indications, as they seem to my associates and me, that somewhat *higher* temperatures than given in the recommendations in the paper are safe for the insulation for emergency use according to the results of the *tests* and *field investigations* made in Chicago and elsewhere. Of course, as indicated in the paper, the critical limiting factor may be the sheath during the usual daily loading which corresponds to the increased maximum allowable loading.

Shanklin refers to the fact that the maximum allowable copper temperatures in Europe are lower than set by the American rules. Our studies of English and continental literature, as well as private information, do not disclose adequate technical explanation for these differences in allowable temperatures. In the successful tests on single-conductor cable at 150 kv to ground at Arnhem, Holland, the temperatures have been usually above the limits allowed by rules either in the United States or in Europe. Furthermore, it is of interest to note that when it comes to other equipment the maximum allowable temperatures in Europe are comparable to those allowed in the United States; and, in that connection, one frequently sees figures such as 100 or 110 degrees centigrade, which is much above the limiting temperatures set for cables in Europe.

It is of interest to note that Shanklin sees no objection to "the use of emergency overload ratings under favorable conditions and where performance can be watched closely." In the paper it was intended to adjust the emergency overload ratings to the field conditions as well as to limitations imposed by the insulation or sheath or both. If the manholes, for example, are small, then the effect of this condition must be taken into account.

Roehmann has requested the derivation of the formulas relating to cable movement. His interest, as well as the interest of others, in this general subject is gratifying, but nevertheless it seems desirable to omit taking the space to present this derivation because of the unusual amount of space already taken by the paper. I shall, however, be glad to send a copy of the derivation to anyone upon request.

Davis' objection to using the same coefficient of thermal expansion for cable as for bar copper (16.7×10^{-6}) seems to be based on erroneous assumptions. He derives a value of 14.5×10^{-6} on the assumptions (1) that the angle of lay of the strands in a conductor is 30 degrees and (2) that the expansion of the conductor is to be found by multiplying the *total length of the strand* by the expansion coefficient. The usual angle of lay of strands is nearer 12 degrees than 30 degrees, which would give a value of 16.34×10^{-6} for the coefficient when calculated by his method. This is only two per cent less than the value used in the paper. The second assumption is not in accordance with the usual practice of multiplying the axial length of the cable by the coefficient to get the expansion. The value given in the paper is correct when used in connection with the axial length of the cable, instead of the total length of the strand.

Regarding the discussion by Thomas as to the limiting induced sheath potential for single-conductor cables, the maximum allowable values set in Chicago were based on extensive laboratory and field tests, as indicated in reference 12 of the paper. For instance, two trial installations in the field were operated at 18 volts to ground in one case and 20 volts in the other case for $1^1/_2$–2 years, and corrosion was found in both cases. It therefore seemed to us from these and other data that normally the sheath potentials to ground should be considerably below 18 volts in order to avoid a-c electrolytic corrosion over a period of many years. It is recognized that in some instances such potentials may be safe, but once corrosion starts, mitigating measures may not stop it entirely. We have, therefore, set a limit of 11 volts to ground for usual daily loading, and periodic examinations of cable under water in manholes have indicated this limit to be reasonable.

When it comes to the personal safety angle in connection with sheath potentials, it should be recognized that the transient sheath voltages may be a matter of several kilovolts instead of just the 200 volts at generated frequency mentioned by Thomas. This fact, plus the fact that there is no considerable difference in the order of magnitude of the transient sheath potentials between bonding systems using the cross-bonding scheme or open-end bonding or sheath-bonding transformers, is given in the paper "Transient Voltages on Bonded Cable Sheaths" in the January 1935 issue of ELECTRICAL ENGINEERING. These transient potentials cause no harm to individuals nor to sheaths, and experience has demonstrated that they will cause no harm to insulators or other accessories provided the presence of the transients is recognized and adequate insulation is provided to withstand them.

Replying to Komives, careful training of cable in manholes has been quite effective in prolonging sheath life. We have standards set up for all types of manholes (straight, *X*, *T*, etc.) and all numbers of ducts. These are closely followed. The desired joint position is accurately indicated on the cable installation print for each job. In the case of manholes not conforming to standard, the cable training is worked out with the aid of a scale model of the manhole.

Regarding the effect of nonfluid joint compounds on the power factor of cable, we get high power factors in solid-type cable adjacent to joints filled with asphaltum-type compounds, but we have never had a failure ascribed to this cause. Nevertheless, as a matter of improvement, we are continuing to give consideration to insoluble compounds.

It has been found also in Chicago that thin joint oil entering solid-type cable has caused increased power factor of the cable insulation, due mainly to contamination of the oil by the varnish of the old-type varnished cambric used in existing joints. This action occurs essentially in manholes where the ambient temperatures are lower than in the ducts and, except for a few special cases, this cable will remain thermally stable to the highest temperatures mentioned in this paper.

The use of the taped joint decreased the possibility of bulging and collapsing of three-conductor joints by permitting the

Maximum Safe Operating Temperature for 15-Kv Paper-Insulated Cables

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THE capital investment in the underground cable system of any large metropolitan utility is so great that any means of increasing its usefulness is of great and immediate interest. The operation of paper-insulated cables at higher copper temperatures than are accepted as normal, offers one obvious means of increasing the usefulness of the cable system where voltage regulation does not limit load.

Previous reports on thermal limits of paper insulation have been presented by Del Mar,[2] Torchio,[3] Roper,[4] Clark,[5] Fisher and Atkinson,[6] and Bush.[7] Electrical and physical characteristics of impregnated paper as affected by temperature were investigated at the Massachusetts Institute of Technology under the direction of a joint committee on research set up by the National Electric Light Association and the Association of Edison Illuminating Companies. This work was reported from time to time over the period between 1921 and 1929.

Paper number 39-70, recommended by the AIEE committee on power transmission and distribution, and presented at the AIEE winter convention, New York, N. Y., January 23-27, 1939. Manuscript submitted November 28, 1938; made available for preprinting January 3, 1939.

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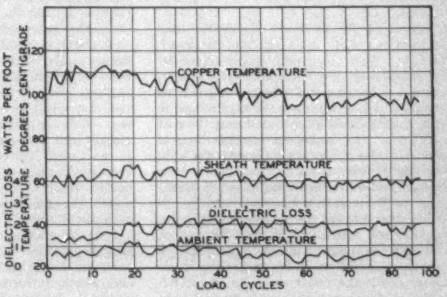
The authors gratefully acknowledge the co-operation of the many individuals in the operating, research, test, and engineering divisions of the company who collectively made possible the carrying on of this study.

1. For all numbered references, see list at end of paper.

Figure 1. Load-test measurements at three phase, 13.6 kv, 60 cycles

Three - conductor 250,000-circular-mil 15-kv cable



About five years ago, the Edison Company in New York started a series of laboratory and field tests to learn the effect of intermittent operation of paper-insulated cables of the 15-kv class at temperatures above the level generally accepted as maximum for their class. This we believe is the only extensive field investigation of the kind that has been made on cable as a unit instead of on constituent parts of the cable and, for that reason, may be of interest.

Laboratory Test

Investigation was begun in January 1934 with laboratory tests on five 50-foot lengths of cable withdrawn from service. The cable was three-conductor round 250,000 - circular - mil paper - insulated belted - construction lead - covered cable which had been in service on the system for about 25 years. For about half of its life, prior to these tests, it was operated at 6.6 kv, 25 cycles, and thereafter at 11 kv, 25 cycles. The cable has rosin-compound-impregnated Manila-paper insulation, 170 mils conductor insulation, 155 mils belt insulation, jute fillers, and 125 mils lead. Examination of samples prior to the testing showed the paper tapes to be wide and badly wrinkled, dry, lifeless, and covered with powdered rosin. A few of the sections examined, however, showed the paper tapes to be fairly well saturated.

The laboratory test connections were arranged so that load current could be circulated in each phase conductor and a three-phase test potential of 13.4 kv, 60 cycles, applied continuously. The load currents were applied for a period of eight hours during each working day and then removed for the remaining period. The values of the current were adjusted to obtain different maximum copper temperatures.

The potheads used on the first sample of cable to be tested were filled with petrolatum. Some of the potheads used were not of an oil-tight type and compound was forced out during the loading cycles. Potheads on the second sample were filled with paraffin in order to see what effect this compound might have

use of a substantially smaller diameter of sleeve than was feasible with the cell-type joints formerly used.

We do not know exactly what effect the ratio of cable diameter to duct size has on cable movement at the manhole. Our data do not show that there is any definite correlation. We would expect less movement in larger ducts. It is difficult to get significant data on this point because we do not have the larger "stiff" cables in very large ducts which could be studied for comparison with similar cable in normal-sized ducts. We do have cables that are small compared with the duct size, such as 4/0 four-conductor four-kv cable in 3½-inch duct, but such cable is relatively flexible, and the ratio of copper cross-section to total weight is low.

Our studies on cable movement and related problems are continuing.

Wiseman, in referring to part III of the paper, inquires as to why the maximum three-hour average load is used in determining the load factor. Step-by-step calculations have been made in the past to determine the maximum temperature based on readings of the current taken every half hour, and it has been found that the resultant temperature is very close to what is obtained by using for Chicago conditions the simple arithmetical average load over the peak three-hour period.

He refers to the possibility of inaccuracy in taking the air temperatures in connection with figures 19 and 20. It may be noted that considerable care was exercised in taking these readings. In fact, the care was greater than may be expected from a field crew when taking temperatures of occupied ducts by the usual methods. As to his further remarks on thermal emissivity, we have found it reasonably correct (see figure 20) to use an emissivity constant approaching 1,200 and have the calculated thermal drop represent the thermal drop from the sheath to the air in the adjacent warmest unoccupied duct.

Table I. Classification of Troubles, Long-Time Test on Three-Conductor 250,000-Circular-Mil Cable

Cause of Trouble	During Test		After Test		Total	
	Number	Per Cent	Number	Per Cent	Number	Per Cent
Cable						
Dielectric failure	16	54	2	17	18	43
Lead-sheath failure	7	23	6	50	13	31
Miscellaneous	1	3	2	17	3	7
Unknown	1	3	1	8	2	5
Joints						
All	5	17	1	8	6	14
Total	30	100	12	100	42	100

on the cable under test because some of the joints on this cable in the field were filled with paraffin. The potheads installed on the remaining three samples were filled with an oil-insoluble hard compound. This prevented the migration of compound into or from the cable during loading cycles. At the end of each loading cycle dielectric power loss, voltage, charging current, and sheath and ambient temperatures were measured.

The curve shown in figure 1 is typical of the values measured on the test samples. The sample for which data are shown in figure 2 failed before the end of the 16th load cycle. An attempt was being made on this sample to operate it at a copper temperature of 140 degrees centigrade. This temperature was at the borderline of thermal instability and slight changes in the load current resulted in a runaway condition and failure.

Examination of this cable at the end of the tests showed severe carbonization. The tapes near the conductor were reduced almost to ash for the entire length of the sample. The cables used for the other tests showed signs of carbonization in each case where the temperature had exceeded 130 degrees centigrade to any extent during the test. One sample whose temperature varied between 120 degrees and 130 degrees centigrade showed no signs of carbonization. The only sample whose temperature never exceeded 115 degrees centigrade also showed no signs of carbonization. At the end of the test, the paper tapes near the conductor on this sample seemed somewhat drier and more brittle than at the beginning of the test. This was the only noticeable change.

The conclusions drawn from these tests were that the practical limit for safe maximum operating temperatures in the field should be 100 degrees centigrade. It was also concluded that if any failures were to occur as a result of cumulative heating from high dielectric loss, they would occur within the first few load cycles, since the trend of dielectric loss showed little tendency to change after the first few test load cycles.

Table II. Failure Rates by Manufacturers, Long-Time Test on Three-Conductor 250,000-Circular-Mil Cable

Manufacturer	Section-Years	Failures per 100 Section-Years	
	Sections	During Test	During Test	After Test
A	40	95	5.3	4.5
B	22	27	3.7	0
C	22	36	39.0	6.3
Other	21	21	0	5.0
Unknown	15	20	25.0	20.0

Long-Time Field Tests on Old-Type Cable

The conclusions based on four months of laboratory operation could be verified only by similar tests carried out under field conditions over a longer period of time. Four 11-kv 25-cycle feeders were selected for the field test. A temperature survey was made along the routes of these feeders in order to determine the existing empty-duct temperatures. These values ranged from 30 to 40 degrees centigrade. Based on this information, a value of current was calculated which would result in a 100-degree-centigrade copper temperature for this cable having dielectric loss characteristics as determined from laboratory tests and for an assumed average empty-duct temperature of 35 degrees centigrade. The computed value of current was 290 amperes and this was the assigned value of loading to be carried on the cable in these feeders. The field tests on the four feeders started in July 1934. These feeders contain a total of about 6½ miles of old 250,000-circular-mil cable.

The feeders under test supplied d-c substations from a generating station. Daily load cycles of 290 amperes on each feeder over an eight-hour period were obtained by using substation tie feeders to transfer load to and control load on the feeders under test. The test loads were not applied on week ends or holidays, and there were a few short intervals when operating conditions necessitated the omission of the test loads. The week-end periods were utilized to make kenotron tests at 20 kv to ground for five minutes in order to determine whether the insulation resistance changed as indicated by the milliampere leakage current during the test. The values of current measured during these tests show very little change and could probably be accounted for due to variations in temperature. It was further felt that the test might serve a useful purpose in developing incipient failures and thereby avoid some operating failures.

Due to the variations in duct constants and heating from other underground structures, the actual copper temperatures which resulted had maximum values ranging from 78 degrees centigrade to 133 degrees centigrade as determined from calculations based on measured empty duct temperatures obtained at various locations during the testing period.

The last of the original four long-time test feeders containing the three-conductor 250,000-circular-mil cable was taken off test in February 1937, about 2½ years after the test began. The other three feeders had been on test for 1, 1½, and 2 years, respectively.

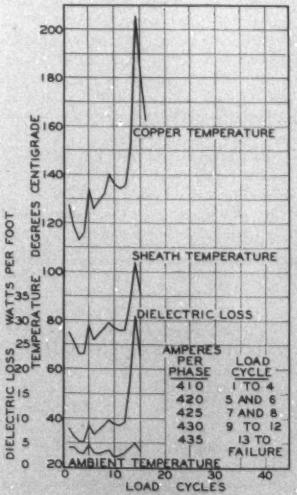


Figure 2. Load-test measurements at three phase, 13.6 kv, 60 cycles

Three-conductor 250,000-circular-mil 15-kv cable

During the testing period a total of 30 cases of failure and removal before failure had developed on the 250,000-circular-mil cable in these feeders. Between the period in which these cables had been removed from test and November 1938,

12 additional failures occurred. A summary of the classification of this trouble is shown in table I.

The cable in the feeders under test was made up principally of three different makes. The cable of one manufacture had an extremely high rate of dielectric failure compared to the other makes of cable. Comparison of cables by manufacturers is shown in table II. The various makes of cable were distributed among the four feeders tested as shown in table III and for comparison the range of duct temperatures in which these feeders operated is shown below the respective feeder numbers. While the one make of cable which showed a very high rate of dielectric failure was confined principally to one feeder, this feeder was installed in duct banks which had lower empty-duct temperatures than the other feeders. It does not seem probable that the high failure rate was due to operating conditions more severe than on the other three feeders tested.

Examination of the cable samples showed that in 14 cases of the 18 dielectric failures evidence of carbonization of the paper and occasionally of the compound appears in the conductor insulation adjoining the burnout area. This carbonization ranged from light and dark colored bands on the tapes to a charred mass of filler in the cable crotch.

In several instances the carbonization was strictly local, suggesting nonuniformity in the cable or excessive local duct temperatures, such as a steam-main crossing might occasion. In fact, six of the carbonization cases were definitely associated with copper temperatures of 110 degrees centigrade or higher as calculated from empty-duct measurements. In the remaining eight cases where carbonization of the paper, as well as of the compound, was found, these sections of cable were not believed to have been operated at temperatures in excess of 100 degrees centigrade during the loading test.

In order that the investigation be not confined solely to those sections of cable which had failed, six sections from these feeders were removed before failure for visual examination of dissected specimens and laboratory tests to determine dielectric loss and thermal resistance of the insulation. The sections selected had been subjected to from 225 to 366 cycles of test loading. There were specimens of each of the three different makes of cable. Physical inspections showed no marked difference in the appearance of the insulation made by any of the manufacturers. Varying degrees of saturation were found but most of the insulation was fairly dry. The compound was frequently found to have become discolored and hardened, particularly next to the conductor. In two instances flecks of carbonized compound were discovered but in one of these cases the carbonized specks occurred at a point in the cable which had been at a higher temperature caused by a steam main. No carbonized paper was found.

The results of laboratory tests on these removed samples of cable showed that their measured thermal resistivity was from 8 to 24 per cent above the value of 700 degrees centigrade per watt per centimeter cube which value had been used in computing the rated current for the load tests. While these test values were higher in each case than those measured on cable samples removed prior to the loading tests no change was made in the value previously used in computing copper temperatures. It is quite possible that copper temperatures may have been a few degrees higher or lower in some instances than those calculated. The dielectric-loss measurements on these samples were different in some cases than the values obtained on samples preceding the starting of load testing at which time a dielectric loss of one watt per foot had been assumed for a copper temperature of 100 degrees centigrade. Typical measured values of dielectric loss for these removed samples are shown in figure 3. These values are shown to indicate the relative variations between makes of cable. The actual dielectric loss when operated at 11.4 kv, 25 cycles, would be approximately one-half of these values. It will be noted that the samples of cable of manufacturer *C* are among the highest values for each temperature. This was the make of cable which had the highest dielectric-failure rate.

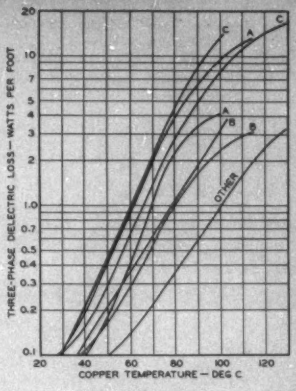


Figure 3. Dielectric loss measurements, 13.6 kv, 60 cycles

Three-conductor 250,000-circular-mil 15-kv cable

Several specimens of 250,000-circular-mil cable from a faulty feeder which had not been subjected to load tests were examined. Striations of carbonized paper and compound were noticed near the fault and evidences of carbonized paper near the conductor were found at several other locations. The presumption is that this portion of the feeder had been subjected to overloads at some previous time. The presence of carbonized paper in these samples serves as a warning that the test load cycles must not be charged too readily with the full responsibility for similar conditions in samples from the tested feeders.

Table III. Distribution of Failures in Feeders, Long-Time Test on Three-Conductor 250,000-Circular-Mil Cable

	Number of Sections Tested and Number of Faulty Sections							
	Feeder No. 1		Feeder No. 2		Feeder No. 3		Feeder No. 4	
Manufacturer	Tested	Failed	Tested	Failed	Tested	Failed	Tested	Failed
A	16	1	11	2	4	0	18	2
B	3	0	2	1	18	0	1	0
C	16	13	3	1	3	0	0	0
Other	0	0	1	0	20	0	0	0
Unknown	0	0	2	2	11	2	2	1
Average empty-duct temperature	31		35		35		30	
Maximum empty-duct temperature	37		37		38		42	

Long-Time Field Tests on Modern-Type Cable

After nine months of load cycle testing on old 250,000-circular-mil cable, it was decided that similar long-time tests should be started on a small amount of three-conductor 600,000-circular-mil shielded cable, 220 mils insulation, 125 mils lead, in order that it might be pos-

Table IV. Classification of Trouble During Test, Long-Time Tests on Three-Conductor 600,000-Circular-Mil Cable

Cause of Trouble	Number	Per Cent
Cable		
Dielectric failure	0	0
Lead-sheath failure	8	62
Miscellaneous	2	15
Joints		
Cracked sleeves	3	23
Total	13	100

Table V. Distribution of Failures as to Time of Occurrence, Three-Conductor 250,000-Circular-Mil Cable on Short-Time Tests

	Number of Failures	Per Cent
During test period		
Preliminary kenotron test	3	3
During loading test	21	24
Final kenotron test	7	8
	31	35
After load testing		
Operating failures	22	25
Test failures	29	34
Removals before failure	5	6
	56	65
Total	87	100

sible to determine whether or not the effects of these heavy loads on modern-type cable is different from the effect on the older type of cable.

Such a test was started in April, 1935, on two miles of this cable in one feeder which had been in service about five years. The cable had been purchased in 1929 and 1930. Joints on this cable were filled with petrolatum. The feeder containing this cable was tested until August 1936 and again from October 1937 to May 1938, a period of about two years. More of this type of cable, 4,000 feet long, was put on test in December 1937 and is still under test. The interruption of the test on the first feeder was made necessary by operating conditions.

During the period of these tests a total of 13 troubles have developed. One trouble developed on this cable during the period when the feeder was temporarily removed from test. The causes of the troubles which occurred on this cable during the tests are shown in table IV.

The trouble rate on this cable during the period that the test was in progress was high compared with similar cable not under test. During the interval the test was discontinued, there was a marked decrease in failures in this cable.

An examination of the sheath and insulation was made on all cable removed from service. The sheath in some cases was slightly swollen but not excessive as might be attributed to a "ratcheting" action as occasioned by successive load cycles. The cable insulation in all cases was in good condition and showed no signs of carbonization. The troubles caused by cracked and swollen joints cannot be attributed definitely to the load test as the joints in manholes were not inspected prior to the test and several similar cases have been found on cable operated at normal copper temperature. It seems quite probable that a great number of sheath failures can be directly attributed to the test loading.

Short-Time Field Tests

After about nine months' experience with cyclic loading to 100 degrees centigrade copper temperature on the four feeders containing 250,000-circular-mil cable, it was found that most of the failures had been due to dielectric heating, and relatively few were due to mechanical trouble. It was tentatively decided to rate cable of this type and vintage for emergency operation at current values corresponding to 100 degrees centigrade copper temperature. The feeders containing such cable were for the most part made up with cable having larger-size conductors than 250,000 circular mils, and it was felt that these higher operating temperatures could be tolerated, even should they cause increased operating failures, in order not to unduly limit the capacity of the feeders.

Beginning April 1935, a series of short-time field tests was begun. This was undertaken because it was felt undesirable to increase the rating of some 74 feeders containing three-conductor 250,000-circular-mil cable similar to that in the long-time test feeders without attempting to precipitate incipient failures which might otherwise occur at a more inconvenient time from the operating standpoint. Cyclic loads calculated to result in maximum copper temperatures of about 100 degrees centigrade were applied for eight hours each working day for two weeks. Sixty-six of a total of about 74 feeders were tested in this manner. The remaining feeders could not be tested because of operating difficulties in obtaining the desired loads. There is a total of 72 miles of three-conductor 250,000-circular-mil cable in the tested feeders. The ratings of about 50 feeders containing three-conductor, 250,000-circular-mil cable have been increased to a value of current corresponding to 100-degree-centigrade copper. It was proposed that the rating of the other feeders be increased later. Notwithstanding the increase in the rating, it was found in December 1937 that the loads actually carried had increased very little above those which these feeders carried prior to the testing. As a result, the operating record of these cables since the conclusion of the testing cannot be considered indicative of their operation at loads corresponding to 100 degrees centigrade. Eighty-seven cases of trouble have occurred on this type of cable in these 66 feeders during a period of $3\frac{1}{2}$ years. Sixty-nine of these were cable failures and 18 were joint failures. The distribution of failures as to time of occurrence is shown in table V. The ascribed causes of failure in cable are shown in table VI.

In two of the cases where the cause was ascribed to dielectric failure, the cable had carried loads far greater than the test load and in two other cases the faulty cable was found to have been near steam-main crossings which increased the duct temperatures to values which gave calculated copper temperatures over 100 degrees centigrade.

Carbonization of the insulation adjacent to the failure or in end samples was observed in 28 cases. The degree of this carbonization varied over the same wide range noted in the discussion of the long-time tests on this cable. The cable insulation in many of the remaining cases of failure was found to be generally desaturated and dry and carbonized compound was often found.

The results obtained on these tests

Table VI. Classification of Troubles, Short-Time Test on Three-Conductor 250,000-Circular-Mil Cable

Cause of Trouble	During Test*		After Test		Total	
	Number	Per Cent	Number	Per Cent	Number	Per Cent
Dielectric failure	20	80.0	24	54.5	44	63.7
Lead-sheath failure	2	8.0	12	27.3	14	20.3
Miscellaneous	3	12.0	4	9.1	7	10.2
Unknown			4	9.1	4	5.8
Total	25	100.0	44	100.0	69	100.0

* Includes failures due to kenotron tests which were made before and after the two-week loading periods.

Table VII. Comparison of Failure Rates

Failure Rates per 100 Mile-Years of Operation

Year	All 250,000-Circular-Mil Belted Cable			All Cable Operating at 11.4 Kv Except Three-Conductor 250,000-Circular-Mil Belted		
	Cable	Joint	Total	Cable	Joint	Total
1931	32.0	3.5	35.5	11.7	6.0	17.7
1932	22.9		22.9	9.0	4.5	13.5
1933	18.5	4.8	23.3	8.8	3.1	12.0
1934*				9.7	3.6	13.3
Jan.–May* 1934	15.9	4.4	41.8			
June–Dec.* 1934	38.8	3.0				
1935*	66.8	17.6	84.4	16.1	5.9	22.0
1936*	55.6	4.1	59.7	13.0	5.5	18.5
1937*	12.8**	9.5**	22.3**	12.4	2.7	15.1

* These rates include removals before failure. Long-time load tests were in progress on one or more feeders between July 1934 and February 1937. Short-time load tests were in progress on one or more feeders between April 1935 and July 1937.

** Rate obtained over period from May 1, 1937 to October 1, 1938.

indicate that the failure rate during the heavy-load testing was several times the failure rate usually experienced with that type of cable when operated normally. The failure rates of these same cables after conclusion of the testing was lower than the value during the testing and tended to approach that usually experienced with this type of cable as normally operated. The comparison of failure rates between old 250,000-circular-mil cable and all other cable operated at 11.4 kv is shown in table VII. A period of time was included to show the operating experience prior to and subsequent to the load testing. It will be noted that the vintage of cable tested had had a consistently higher failure rate than other cable before the test. During the test period, the failure rate increased markedly and at the conclusion of the tests it had closely approached the average of the other cables.

Conclusions

1. Operation over a continuing period of load cycles to copper temperatures of 100 degrees centigrade of old types of paper-insulated cables which were dry and contained rosin, results in a marked increase of dielectric failures.

2. Similar operation of modern well-impregnated paper-insulated cables resulted in no failures caused by dielectric heating or aging.

3. Both old types of cable and modern types of cable had an increase in the rate of failure due to wearing and cracking of the lead sheath when operated at these load cycles.

4. It is our opinion that the occasional operation of paper-insulated cables during emergency conditions to copper temperatures as high as 100 degrees centigrade can be justified where a small number of sections of cable in any feeder otherwise set up loading restrictions.

5. It is our opinion that those types of modern cable which provide means for taking care of the expansion and contraction of the cable compound, such as not to unduly stress the lead sheath, could be operated repeatedly to copper temperatures as high as 100 degrees centigrade.

6. It is our hope that others may be interested in carrying on similar operating experience on cable systems of this and other voltage classifications, in order to obtain a more widespread knowledge of practical operating limitations for paper-insulated cable.

Bibliography

1. Permissible Temperatures of Paper-Insulated Underground Cables, NELA *Proceedings*, 1921, page 1306.

2. Maximum Safe Operating Temperatures of Low-Voltage Paper-Insulated Cables, **Del Mar.** NELA *Proceedings*, 1921, page 97.

3. Permissible Operating Temperature of Impregnated-Paper Insulation in Which Dielectric Stress Is Low, **Torchio.** AIEE Transactions, 1921, page 107.

4. Permissible Operating Temperature of Impregnated-Paper Insulation in Which Dielectric Stress Is Low, **Roper.** AIEE Transactions, 1921, page 131.

5. Notes on Effect of Heat on Impregnated-Paper Cable Insulation, **Clark.** AIEE Transactions, 1921, page 137.

6. Effect of Heat on Paper Insulation, **Fisher and Atkinson.** AIEE Transactions, 1921, page 143.

7. Research to Determine Limiting Temperatures of Paper-Insulated Lead-Covered Cables, NELA *Proceedings*, 1922, page 552.

8. Massachusetts Institute of Technology Tests on Effect of Heat on Paper, NELA *Proceedings*, 1921, page 1726.

9. Massachusetts Institute of Technology Report on Deterioration of Impregnated Cable Paper Subjected to Temperature Only, AIEE Journal, 1925, page 508.

10. Research on the Characteristics of Impregnated Paper-Insulated Cables, NELA *Proceedings*, 1927, page 1444.

11. Rate of Deterioration of Impregnated Wood-Pulp Cable Paper Subjected to Heat Only, NELA *Proceedings*, 1929, page 1493.

12. Tests on Oil-Impregnated Paper, **H. H. Race.** Electrical Engineering, July 1937, pages 845–9.

Discussion

L. I. Komives (nonmember; The Detroit Edison Company, Detroit, Mich.): It would be interesting to know the distribution of cable failures due both to the dielectric and to the lead sheath in regard to its location, that is, what percentage of failures were in the manhole, near the manhole in the duct, and in the duct section.

Conclusions drawn in the paper seem to be less enthusiastic than in the presentation by the author. However, in either case, the author and his company should be congratulated in taking such a bold step to find out the economical life of a highly loaded cable.

It seems to be a moot question whether the fact that an overloaded cable cannot be salvaged to be reused was taken into consideration when economical loading of cables was considered by the author.

G. B. Shanklin (General Electric Company, Schenectady, N. Y.): I desire to discuss briefly maximum safe operating temperature of underground cable as covered by the two outstanding papers presented by Franklin and Thomas, and Halperin.

Each of these two papers has made a valuable contribution to cable engineering. The paper by Franklin and Thomas is outstanding in giving us for the first time a systematic study of controlled overloading of cable under actual field conditions. I have always felt that this problem would never be solved in the laboratory and that practical knowledge could only be gained in the field, because of the large number of variable factors involved. It is not possible to reproduce these in the laboratory.

Mr. Halperin's paper is outstanding in giving us for the first time a systematic study of cable movement under load conditions in ducts. Now that Mr. Halperin has placed this problem on a scientific basis we need an extension of this information covering all possible conditions of field service. The severe duty requirements on lead sheath, especially with modern, well-impregnated cable, represents a limiting factor in determining maximum safe operating temperature for cable.

An analysis of the data records in both papers leads to the same important conclusion, which is, that when underground cables are loaded above what we now consider normal loads, there is a noticeable increase in the rate of service failures. This is true whether the cable is of the old poorly impregnated type or the modern well-impregnated type using thinner compound. Overloading of the older cable leads to dielectric loss failures and fatigue of the lead sheath due to cable movement. Overloading of modern cable causes an even greater burden on the lead sheath, and the majority of service failures are due to lead-sheath troubles. With modern cable, overloading causes greater stretching of lead sheath which not only adds to the sheath troubles mentioned but aggravates migration of compound, leading to ionization damage in the drained sections of cable. Thinner insulation and higher working stresses in modern cable do not allow pronounced drainage of this kind, and this can only be avoided by keeping the operating tempera-

tures within reason. The same lesson has been learned in Europe, and maximum allowable copper temperature is invariably lower than allowed by our present standard rules.

At the AIEE winter convention in 1921 a symposium of six papers was presented on exactly the same subject. In discussing these papers the present writer summarized the various factors involved and then made the following statement:

> When these factors are considered, it is apparent that the temperature limit of (low-voltage) paper cable insulation should be something less than 105 degrees centigrade. If the temperature limit of 85 degrees centigrade is to be raised, this change must be approached with caution and an increase to 90 degrees or 95 degrees centigrade is all that should be attempted until more is known of the subject.

Thanks to the authors of these two papers and the experience we have all gained since 1921, we now know more about this subject. Nevertheless, the above statement still holds. The margin for temperature increase to take care of emergency loads is without question quite narrow, and the data records in the two papers by Franklin and Thomas, and Halperin show that an increased rate of service failures must be accepted.

The writer does not believe that the cable industry is yet in a position to draw up safe emergency overload ratings for cable that approach the temperature limits suggested by these two papers, in the order of 100 degrees centigrade for 15-kv cable. This will definitely mean an increase in service failures. The burden on the lead sheath is greater than it used to be. If this is a limiting factor, as indicated by these two papers, we must know more about the general conditions of cable movement and training of cables in manholes. Many of these manholes around the country are relatively small and extremely crowded, with short radius of bend on the cable. In drawing up national standard rules we must protect both the users and the manufacturers who must meet these kinds of conditions. This in no way precludes the use of emergency overload ratings under favorable conditions and where performance can be watched closely. These special conditions cannot very well be included, however, in standard rules covering all possible field conditions.

Temperature increases for emergency load rating as proposed by Mr. Halperin are outlined in table X of his paper. In my opinion the proposed temperatures should be decreased by at least five degrees centigrade in some cases and by ten degrees centigrade in other cases for safe use around the country. This would mean that there would be no margin at all for 66-kv single-conductor cable. The present normal load limit of 60 degrees centigrade for cable of this voltage rating is already too high.

Wm. A. Del Mar (Phelps Dodge Copper Products Corporation, Yonkers, N. Y.): The papers by Franklin and Thomas and Halperin present a mass of data tending to show that the present standard temperature limits for paper-insulated cables are not sufficiently high, as far as the dielectric is concerned but, if materially exceeded, may lead to early sheath and joint trouble. Such developments as may occur in solid-type cable in the near future are more likely to increase the stability of the dielectric than the life of the lead and, therefore, will not raise the temperature limit.

Moreover, some effects not anticipated may limit the tendency toward higher temperatures such as, for instance, the cumulative effect of soil drying around duct lines operated at very high temperatures or the eventual rise in power factor which must result from ionization during cold periods of the exaggerated load cycle. It must be remembered that the tests were at rated voltage, not under accelerated aging conditions as far as voltage is concerned, and that a two-year test only indicates what will happen in two years, not five or ten years. Accelerated aging tests at voltages well above those of normal operation do not show much change in power factor or hot-spot-temperature development in the early stages but, at some unexpected moment, start up rapidly, as a prelude to failure.

J. A. McHugh (Consolidated Edison Company of New York, Inc., New York): Outstanding features of this paper appear to be the importance of the condition and mechanical construction of paper insulated cables in determining their ratings.

1. The cables of the vintage of a quarter century ago show, as the authors point out, a wide difference of present condition, overloads sustained in more rigorous years being a serious factor. Perhaps distention of the sheath and absorption of excess compound by the paper are causes of their high dielectric loss. The use of the load cycle test at high temperature appears, from the data of table V, to be effective in precipitating voltage-test failures and removing the poorer cable from service at convenient intervals.

2. The modern cables, of essentially "hard" core construction, are limited in their ratings by the sheath, as the authors have indicated in table IV.

3. Conclusion 5 regarding modern cable which provides means for taking care of the expansion and contraction of the cable compound is inevitable. Distinction might well be made between constructions which simply control the internal hydrostatic pressure and those which also maintain continuous impregnation, in further investigations.

It is to be hoped that this investigation, so logically developed, will be helpful in increasing the economic availability of the improved cable constructions.

E. W. Davis (Simplex Wire and Cable Company, Cambridge, Mass.): Conclusion number 4 states that 100 degrees centigrade is justifiable for occasional operation. It is interesting to notice how closely this represents the general opinion of 18 years ago in 1921, as indicated by the AIEE symposium on this subject at the winter convention of that year, particularly if allowance is made for the reasonable differences of opinion that existed then.

The authors' test results indicate that the principal limitation to more severe service is sheath trouble rather than actual temperature deterioration of the paper. This is further reason for the present-day tendency to improve the quality of lead sheath and to develop superior types of sheath where possible.

In connection with the interesting superiority of the new cable over the old we are wondering to what extent this is due to the fact that the new cable was type *H* and the old was belted. Other things being equal, type *H* cable is somewhat superior to belted in allowable operating temperature.

Herman Halperin (Commonwealth Edison Company, Chicago, Ill.): The information, given in this paper, on trials in the laboratory and in service of unusually high operating temperatures for high-voltage cables, constitutes an important and comprehensive contribution on the subject.

The laboratory tests show that temperatures over 130 degrees centigrade are too high for these old rosin-impregnated transmission cables. However, this value is considerably above the present limit of about 75 degrees centigrade for the cable involved, and much can be gained by using some limit between these two values.

In the field tests the authors assumed that the dielectric losses amounted to one watt per foot although their figure 3 shows much higher measured values. Also, the authors found that the thermal resistivities of the insulation were from 8 to 24 per cent higher than the values that they had assumed.

The authors state that in eight cases carbonized paper was found in cable that was believed to have operated at temperatures less than 100 degrees centigrade. Could not these temperatures have been much higher, also, due to higher values of dielectric loss and thermal resistivity than those assumed?

The paper indicates that high rates of trouble occurred during the overload tests but that some weeding out of weak spots occurred with a decrease in troubles for a short time after the tests. The authors seem to suggest that the weak spots be eliminated by an overload test before the emergency ratings are increased. The emergencies during which the temperatures might approach the limits occur at very infrequent intervals. Probably by the time the occasion arrived, other weak spots would have developed. To be effective, then, the elimination testing would be necessary at regular periods.

Trials of higher temperatures of the kind discussed constitute an important step toward more economic use of underground cables. For full effective use of the results, more detailed analysis of the troubles experienced seem necessary, especially in regard to the increases in troubles due to ionization, dielectric losses, sheath cracks, etc., incidental to operation at the increased temperatures.

W. F. Davidson (Consolidated Edison Company of New York, Inc., New York): In support of the data presented in substantiation of the suggested higher operating temperature for paper-insulated cable, I should like to present some data secured about five years ago in connection with a rather extensive investigation of 27-kv paper-insulated cables. The particular study was initiated for the purpose of determining the practicability of reducing insulation thicknesses but as it progressed it became apparent that the most valuable information was concerned with operating temperature limits. The cables were three-conductor 350,000-circular-mil shielded type with 280 mils insulation. Samples were

made by two manufacturers each of whom supplied approximately 4,000 feet. Cables for test were installed in the street and in addition 100-foot lengths were tested by load cycle procedure in the laboratory. The number of daily load cycles ranged from 109 to 114. Maximum load temperatures varied from 70–75 degrees centigrade to 100–105 degrees centigrade with a few load cycles falling within other temperature ranges. The principal criteria of cable performance were the increase in dielectric loss and the reduction in life of residual samples when tested at room temperature and four times rated voltage. An examination of the detailed test results shows that the room temperature dielectric loss was practically unchanged as a result of this load cycle testing. There was a progressive increase in the dielectric loss at elevated temperatures but an analysis of the data has failed to show any clear cut difference in the rate of increase during the 60 load cycles in temperature range 70–75 degrees centigrade as compared with the 35 or 40 load cycles when temperature ranged 100–105 degrees centigrade. Such differences as may exist are obscured by the inevitable variations in observed values.

After completing the load cycle tests, five-foot specimens were removed and tested to destruction at four times rated voltage to obtain a measure of the comparative residual life. For one make of cable, the duration to failure was 4.5 hours as compared with more than 570 hours for samples that had not been subjected to load-cycle testing. For this make of cable, the dielectric loss at 80 degrees centigrade had increased to a value 90 per cent above that obtained on tests made at the factory. For the other make, the life of samples after load cycle aging was 11 hours as compared with 40 hours for cable which had not been subjected to the test and the dielectric loss at 80 degrees centigrade had increased sixfold.

C. W. Franklin and E. R. Thomas: In reference to the question of L. I. Komives regarding the distribution of cable failures as to location of failure, 85 per cent of the dielectric failures occurred in the duct, 10 per cent in the manhole, and the remaining at the duct edge or unknown. Similarly 51 per cent of the sheath failures occurred in the manhole, 40 per cent at the duct edge, and the remaining in the duct.

We are in agreement with E. W. Davis that sheath troubles constitute one of the major limitations in the operation of solid-type paper-insulated cables and that everything possible should be done to improve the quality of cable sheaths. While the dielectric failures found during the heavy load testing were confined entirely to old belted cable, and while age and type of cable both probably were contributing factors, we feel that the age of the cable more than the type of cable was the major contributor to the dielectric failures. The impregnating compound used in cables of the vintages tested had dielectric loss characteristics which rose very sharply with temperature and thus tended to make for greater instability of cable operation at the higher temperature levels.

In reference to Herman Halperin's comments regarding the dielectric loss values used, the test values shown in figure 3 were measured at 13.6 kv, 60 cycles, while the cable under test in the field was operating at 11 kv, 25 cycles. The average dielectric losses assumed to be about one watt per foot at the operating conditions are believed to be in agreement with data obtained on test lengths. The eight cases where carbonized paper was found in cable which was believed to have operated at temperatures less than 100 degrees centigrade are based on assumed values of dielectric loss and thermal resistivities. It is recognized that deviations in these latter quantities may easily have been of the order of ten per cent. Considering these deviations and measured duct temperatures we believe that during the test period these particular cables had not exceeded the 100 degrees centigrade copper temperature. It is quite probable that these cables some time during previous periods of operation may have been subjected to loads which might have caused carbonization of paper to develop. The use of the high-load tests for a short time on the various feeders was believed to be a satisfactory way of eliminating those sections of cable having unstable dielectric-loss characteristics when operated at copper temperatures of 100 degrees centigrade. The test, however, was not intended to determine the thermal limitations along the particular feeder as these had previously been checked by temperature survey. We did feel that this method of test would show up existing unstable cable and that it would not necessarily have to be repeated at any particular period unless it was felt that there was progressive continued deterioration going on in the cable on the feeder.

The data on aging tests conducted on 27-kv cable which W. F. Davidson reported is interesting in showing that the elevated temperature operation did not tend to show a decrease in dielectric stability.

In answer to W. A. Del Mar, we have not experienced the effect of soil drying around our duct lines in such a manner as to create an unstable thermal condition for the duct bank. The fact that these load-cycle aging tests were conducted at normal voltage seems to us to be more convincing evidence of the cable operation ability than short-time tests at overvoltages.

We are in agreement with G. B. Shanklin that paper-insulated cable can well be operated at temperatures of from 90 to 100 degrees centigrade without probable injury to the dielectric but that cable-sheath design and technique of manufacture constitutes the greatest drawback to operating our existing cables at these temperatures.

In closing, we feel that as the result of the papers presented on cable operation at the higher temperatures and the resulting discussion of these papers, we come to the generalization that oil-impregnated paper insulation as used in modern cables is not in itself affected when operated at temperatures up to 100 degrees centigrade but when insulation is incorporated as an integral part of cable it may be subjected to some increase in deterioration due to resulting void spaces which may form due to heating and cooling cycles. The sheath problem, on the other hand, is one of a material limited in mechanical strength and affected more from stresses set up in it due to changes in loading than to the magnitude of the temperature. A satisfactory solution of our cable-sheath problem is probably of more immediate concern in securing a more economical high-voltage cable than the development of improvements in oil and paper dielectric.

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BY THE HISTORY OF ITS PERFORMANCE

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Industrial Notes

Utilities Order Electrical Equipment.—Two nearly identical 35,000-kw, hydrogen-cooled turbine generators, have been ordered from the Westinghouse Electric & Mfg Co., by subsidiaries of the Commonwealth & Southern Corp. One unit will be installed in the Peoria (Ill.) plant of the Central Illinois Light Co., and the other in the Toronto (O.) plant of the Ohio Edison Co. Both machines will be similar in construction to the 9 Westinghouse hydrogen-cooled generating units now in service. They are rated at 43,750 kva, 3,600 rpm, 80 per cent power-factor, three-phase, 60-cycles and have direct-connected main and pilot exciters. It is expected that both machines will be installed by mid-summer next year. . . . . A 3,000-kw, 600-volt ignitron rectifier has been purchased from Westinghouse by the Wisconsin Electric Power Co. This unit will be installed at the Commerce Street power plant in Milwaukee and will feed into the 600-volt station direct-current bus, and deliver power for street railway service. The unit will be installed by the end of this year. . . . . The Westinghouse radio division, at Baltimore, has received an order for carrier-current communication equipment for the Bonneville, Oregon, project. The equipment will consist of 3 standard Westinghouse transmitter-receiver units, two being of 20-watt power and one of 150 watts. The order also includes all necessary coupling capacitors, line wave traps, and line tuning units. This installation will provide communication from the Bonneville power house to Eugene, Oregon, via North Vancouver, Washington, a total distance of 156 miles. Communication will be possible over the carrier system from any point to either of the other two.

Uptegraff Sales Appointment.—J. G. Green, Oliver Bldg., Pittsburgh, Pa., has been appointed sales representative by the R. E. Uptegraff Mfg. Co., transformer manufacturers, Scottdale, Pa.

New DuMont Sales Manager.—The appointment of Mark B. Lajoie to the post of general sales manager has been announced by the Allen B. DuMont Laboratories, Inc., of Passaic, N. J. He succeeds Leonard F. Cramer, resigned.

General Electric Appointment.—Manly E. Lord, of the G-E Schenectady Works, has been appointed manager of the Fort Wayne Works, to succeed Neil Currie, Jr., who has become assistant to the vice-president in charge of manufacturing.

Representatives Appointed.—Frank L. Frable, 100 W. Monroe St., Chicago, has been appointed to represent The Standard Transformer Co., Warren, Ohio, in Illinois, the southern part of Wisconsin and northern Indiana. The Diesel Power Co., 306 E. 4th St., Tulsa, Okla. has been appointed representative for the state of Oklahoma.

Trade Literature

Graphic Instruments.—Catalog 830, 4 pp. Describes recording ammeters, voltmeters, wattmeters, power factor meters, etc. Roller-Smith Co., Bethlehem, Pa.

Arc Welders.—Bulletin GEA-3042A, 20 pp. Describes new, Thyratron-controlled, automatic arc welding equipment for production purposes. General Electric Co., Schenectady, N. Y.

Airbreak Switches.—Bulletin 325, 8 pp. Describes a complete line of side opening, airbreak switches; three types are covered. Electrical Engineers Equipment Co., Melrose Park, Ill.

Phantom Loads.—Cat. 1, Sec. 1D, 16 pp. Describes numerous types of portable phantom loads, including several new additions to previously available instruments for meter testing. The States Co., Hartford, Conn.

Cable Sheathing.—Bulletin, 16 pp. Describes a dual mechanical and chemical treatment that provides cables with lead sheaths free from laminations and uniform in structure from end to end. Included is a complete text of a paper on the subject, by Dr. R. J. Wiseman, Chief Engineer, and presented at the recent summer convention of the AIEE. The Okonite-Callender Cable Co., Inc., Passaic, N. J.

Fibre Insulation.—Bulletin 4 pp. Describes and illustrates applications of vulcanized fibre grommets, washers, bushings, etc., for electrical insulating purposes. Wilmington Fibre Specialty Co., Wilmington, Del.

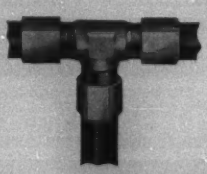
Low Voltage Cutouts.—Bulletin 215C, 4 pp. Describes 6 low voltage cutouts for 110–220-volt distribution service; rating—250 volts, 100 amperes, interrupting capacity, 5,000 rms amperes. Schweitzer & Conrad, Inc., 4435 Ravenswood Ave., Chicago, Ill.

Solenoids.—Catalog, 8 pp. Describes custom-built solenoids, coils, and transformers. Includes diagrams showing design and performance, and illustrates applications of solenoids to modern machines. Dean W. Davis & Co., Inc., 545 W. Fulton St., Chicago, Ill.

Ground Resistance Tester.—Bulletin 150, 20 pp. Describes a new line of "Groundometers,"—direct-reading, ground resistance measuring instruments and accessories, now available at greatly reduced prices. The theory of ground testing and application of equipment is thoroughly covered. Borden Electric Co., Summit, N. J.

Selenium Rectifiers.—Bulletin, 16 pp. Describes in detail a range of selenium rectifiers adaptable to rectification of currents as low as a few milliamperes to thousands of amperes. This equipment, essentially an assembly of strong metal plates, utilizes the rectifying action of metallic selenium. Advantages are said to include long life, reliability in operation, low cost, ability to operate throughout an extremely wide temperature range, compact small size and light weight. Applications include battery charging for many purposes; d-c power supply for electrical and other apparatus and special uses such as a polarizer, spark quencher, tone generator, etc. International Telephone Development Co., Inc., 137 Varick St., New York City.

NATIONAL PRESSURE CONNECTORS



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STRAIGHT SPLICE

SCRUWEDGE LUG

YS CABLE TAP

NATIONAL ELECTRIC PRODUCTS CORPORATION—PITTSBURGH, PA.

Here's a
New 60-Cycle Schering Bridge

For Testing Materials and Measuring Dielectric Properties from Samples of

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CABLES
ELECTRICAL MACHINERY
CERAMICS
FABRICS
PAPER PRODUCTS

To Determine Moisture Content — Composition — Effects of temperature, humidity and voltage gradient

This bridge is very simple to operate and is capable of rapid routine measurements.

The 110-volt a-c line is used as the power source. The voltage across the material under measurement can be varied from zero to ten times the line voltage. Input and output transformers are astatically wound and the instrument is electrostatically shielded; external 60-cycle fields do not affect the bridge and the leads. For normal measurements no guard circuits are required. The bridge has a capacitance range from 0 to 1,000 $\mu\mu$f.

TYPE 671-A SCHERING BRIDGE..... $325.00

Write For Bulletin 491 For Complete Information

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Cambridge, Massachusetts

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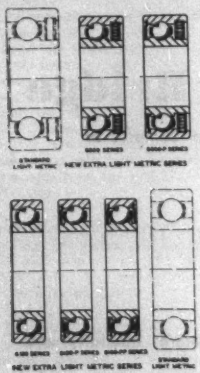
MANUFACTURERS of PRECISION ELECTRICAL LABORATORY APPARATUS

New Products

Angle Socket.—The National Electric Products Corporation, Fulton Building, Pittsburgh, Pa., has recently added to its "Plug-in" strip line a new, No. 971-1, angle socket, which it is claimed makes "Plug-in" strip

the most flexible strip now available for lighting arrangements. The accurate, factory-made 6-inch spacing guarantees uniformity and eliminates careful measurement. Lumiline, tubular and standard shaped lamps may be interchangeably used and lighting arrangements altered at will.

New Ball Bearing Series.—Two new series of extra light ball bearings have been made available by the Norma-Hoffmann Bearings Corp., Stamford, Conn., and are particularly applicable in portable tools and other small



high-speed units in which minimum weight is sought, center distances are restricted, and where space is limited. The sections illustrated show the five types in these two new series, together with a section of a standard light ball bearing for purposes of comparison. In the "6000" series felt-sealed bearing, furnished with single felt seal as "6000," or with felt seal and side plate or shield as "6000-P"—the sealing devices are wholly within the confines of the bearing and therefore not exposed to injury. The felt seals are firmly held in the grooves of the outer ring, but are removable to permit examination, cleaning or relubrication of the bearing. The wide, solid inner and outer rings make housing inserts unnecessary.

Air-Cooled Transformers.—An entirely new line of air-cooled, power transformers, has been developed by The Acme Electric & Mfg. Co., Cleveland, Ohio. Three separate streamlined models cover all standard voltage characteristics from 3/4 to 10 kva in auto and insulated types. The manufacturer claims high, full-load operating efficiency is maintained in this line of transformers through design and construction features, such as full air-draft external ventilation,

specially wound, hand finished coils, insulated between layers with high dielectric strength insulating materials, and cores of thin gauge, low loss steel. New catalog No. 147 illustrates and describes these transformers in detail.

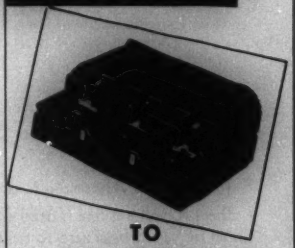
Industrial Noise Analyzer.—An electrical "tin ear" which will enable unskilled workers to detect flaws in running machinery has been introduced by Electrical Research Products, Inc., New York, N. Y. This industrial noise analyzer measures the intensity of sound at any preselected pitch and turns a deaf ear to all other factory noises. Should there be any variation from the normal sound frequency intensities (revealed in previous tests), the dial warns the operator that his machine is defective.

Resistors for Fluorescent Lamps.—Type "FL" resistors, listed under the Underwriters Laboratories re-examination service and specifically designed for approved auxiliaries for d-c operation of fluorescent lamps, have been introduced by the International Resistance Co., 427 No. Broad St., Philadelphia, Pa. These resistors are so constructed as to provide maximum heat dissipation in minimum space. They are of the insulated wire wound type, with 1,250 volt insulation and will operate at a temperature rise of from approximately 40° to 50°C with standard auxiliaries. They are encased in metal boxes of special ventilated construction and sufficiently small to fit in any fixture channel. Over-all box dimensions are approximately 6 3/4" x 1 5/16" x 1 1/16". Total assembled weight of the unit is less than 12 ounces.

Suspension Type Cutout.—The new type, No. 4881-B, cutout introduced by the W. N. Matthews Corporation, St. Louis, Mo., is designed for suspension from the line insulator instead of the conductor. It may be attached to copper or aluminum lines by means of connectors of either metal.

The new cutout is a variation of style Nos. 4881 and 4881-A, which were designed for suspension directly from the conductor, and many of which are now in successful service on rural distribution lines.

TAKE YOUR TROUBLE



TO INSULATOR HEADQUARTERS

• The more complicated your insulator design, the more definite the fact that Universal can supply your needs to your satisfaction. The better quality of Universal "Dry Process" insulators hold to close dimension tolerances. Send specifications for sample and quotation.

THE UNIVERSAL CLAY PRODUCTS CO.
1530 First St. Sandusky, Ohio

Rugged Insulation that
Defies Heat-Distortion
in 1000-kw Rotary Converters

DAY AFTER DAY, the 1000-kw rotary converters in a large eastern railway powerhouse spin constantly at 900 r.p.m., supplying power for trains and trolley coaches. Temperatures in the armature may rise and fall as much as 60°C., yet insulating wedge-bars must remain always firmly-embedded in coil slots . . . unaffected by expansion, contraction or other heat distortion.

That is why the engineers of this electric company have adopted Bakelite Laminated (Micarta) as the standard for converter wedge-bars. This rugged dielectric possesses an expansion coefficient of only .00002 per degree Centigrade, and safely withstands temperatures up to 110°C. And its high mechanical strength and toughness continually withstand the centrifugal load of rotating slot-coils.

Here is but one example of the countless ways in which Bakelite Laminated and other Bakelite plastic materials may help you to improve the insulation and operation of your electrical devices. Write for comprehensive Portfolio 33 of illustrated booklets that offer detailed information on the wide variety of Bakelite dielectric materials now available.

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BAKELITE

PLASTICS HEADQUARTERS

Because of its high mechanical and dielectric strength, Bakelite Laminated (Micarta) was also adopted for these bolt-insulating tubes used in the rotary converter armature shown above.

Bakelite Laminated (Micarta) wedge (3/16"x⅝"x4½") used to insulate armature coils and permanently lock them into position. (Top) Operator driving wedge into coil-slot of 1000-kw, 600v. rotary converter.

CONSULT BAKELITE PLASTICS HEADQUARTERS

More than 2000 plastic materials are available at this single, central source ...phenolic, urea, polystyrene and cellulose-acetate plastics offering wide option of dielectric properties, and resistance to impact, heat, chemicals and moisture. Supplied in many forms including:

IMPREGNATING VARNISH
LAMINATED STOCK SPECIAL CEMENTS
MOLDING MATERIALS

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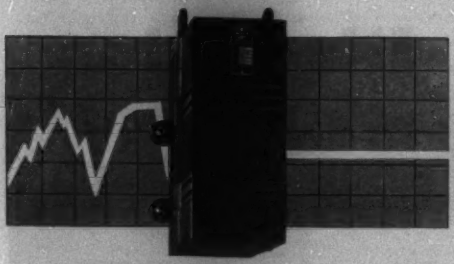
CONSTANT VOLTAGE



TRANSFORMERS

. . . wherever the operation of electrical equipment is affected by line voltage variations this new Sola Constant Voltage Transformer offers a practical solution to the problem. Automatic and instantaneous voltage regulation. No moving parts, nothing to adjust or lubricate.

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AIR COOLED INDUSTRIAL TRANSFORMERS — INSULATED AND AUTO TYPES

LOW VOLTAGE SIGNAL AND CONTROL TRANSFORMERS

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WRITE FOR CATALOG SM-22

SOLA ELECTRIC COMPANY
2525 CLYBOURN AVE. CHICAGO, ILLINOIS

COMPLETE CONTROL UNITS

These Rowan complete control units for 2300 volts are regularly supplied singly or in banks as desired.

The above pictured units each consist of: push-button operated oil immersed starter, fused disconnects, insulated bus, bus insulators, self-contained control potential transformer and a one-man tank lifter. Provisions are made for incoming and outgoing conduits for both motor and control circuits in a sealed-off terminal box.

25th ANNIVERSARY 1914-1939

ROWAN CONTROL

Perfect INSULATING COMPOUNDS for a wide range of temperature

In the Northern States, on the Gulf Coast, and both east and west—Minerallac Insulating Compounds are specified . . . proving that these materials do "stand up" no matter what change in temperature may arise.

• WRITE FOR BULLETIN 186 •

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BURNDY
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BURNDY ENGINEERING COMPANY, INC.
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AIR COOLED *Transformers*

FOR INDUSTRIAL APPLICATIONS

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Ferranti Air Cooled Industrial Transformers are reducing plant operating costs for many manufacturers—and they can do the same for YOU!

Write for new descriptive bulletin listing standard types!

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★ The continued operation of your electric refrigerators or other capacitor-start motor appliances out in the field, is assured by AEROVOX exact-duplicate replacement capacitors. Either through you and your jobbers, or through AEROVOX jobbers, your appliance owners need never fear "orphans." Surely such good will insurance is not to be overlooked.

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Our engineers are ready to collaborate in your motor-starting or other industrial capacitor problems.

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4-inch INSTRUMENTS

are just the right size for small switchboards, panels, "built-in" equipments and many other applications. They are available in surface and flush cases and may now be had in the new *square cases*, as illustrated.

The line includes both *direct and alternating current* ammeters, microammeters, milliammeters, voltmeters, millivoltmeters, single *and polyphase* wattmeters, frequency meters and pyrometers.

Long scales, exceptionally high accuracy and illuminated dials (if ordered) are some of the outstanding features of these instruments.

Complete listings and technical details are given in Catalog AE-48-a, *which will gladly be sent on request.*

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A companion line of 3′ instruments is shown in this same Catalog. The 3′ instruments are a little smaller than the 4′ ones but have the same high qualities.

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Electrical Measuring and Protective Apparatus

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Field and construction men such as construction engineers, construction foremen, carpenter foremen, foremen rodmen (reinforcing steel), etc. Only men who have had extensive experience in their particular field desired. Applicants must be American citizens (final papers) preferably under 45 years, in good health. Free steamship transportation from New York or New Orleans, salary beginning sailing date. For further particulars write "Chief of Office, The Panama Canal, Washington, D. C." giving brief statement of training and experience.

Employment Bulletin

Engineering Societies Employment Service

MAINTAINED for their members by the national societies of civil, mining, mechanical, and electrical engineers, in co-operation with other organizations. An inquiry to any of the three offices will bring full information.

A weekly bulletin of engineering positions open is available to members of the co-operating societies at a subscription of $3 per quarter or $10 per annum, payable in advance.

In the interest of effective service, it is essential that members using the employment service keep the bureau office serving them advised at reasonable intervals concerning their availability for employment, concerning any change in status, and immediately upon acceptance of any employment.

Employers interested in the following announcements should address replies to the key numbers indicated, and mail to the New York office.

Men Available

R.E. SOUND AND PROJECTION ENGR, 28. Desires pos in electronic field, preferably in the East. Familiar with motion picture sound work and theatre constr; 8 yrs draftg exper. E-516.

GRAD E.E., married; 12 yrs exper elec constr, gen wiring, theatre, church and indus ltg. Some draftg exper. Has energy and administrative ability. Desires pos with engg future. E-521.

B.S.E.E., Bucknell, 1935, grad work. Now teaching (3 yrs) elec constr and math in vocational high sch. Exper radio, sound, projection eqpt, testg. Interested in des, radio, electronics, sound, instruction. E-519.

B.S.E.E., 1939, single, 22. Specialized pwr and radio engg; 18 mos co-operative work. Tau Beta Pi, Eta Kappa Nu. Desires pos as jr engr with advancement; location immaterial, salary secondary. E-517.

B.E.E., Catholic Univ, '37, 22, single; 2 yrs exper in elec constr. Desires pos in constr work. Location immaterial. E-518.

GRAD E.E., Swiss Federal Inst Tech, 1937; single, 26; one yr pub util USA; 1½ yrs shop exper as student engr; summer exper on test floor. Speaks German, French fluently. E-523.

RECENT GRAD, BSEE Union '39, good grades, some surveying exper, desires work as jr engr with a mfg co or util. E-524.

E.E., M.E., 30, married. B.S. 1935, Univ Cal; 2½ yrs foundry estimating, sales, maintenance; 2½ yrs indus chem plant draftg, des, constr. Desires sales, mech engg pos with advancement. Location, No. Cal. E-526-358-C-6-San Francisco.

E.E. 34, married, Univ Minn 1928; 6 yrs util, indus electrician, foreman, relays, control wiring; 5 yrs operator, supt 30,000 KW hydro, desires control, constr engg or supervision elec maintenance. E-522-399-C-1-San Francisco.

B.S.M.E., Harvard '27; NY State license; one yr instructor Harvard; 10 yrs Bell system; now employed; desires mech or elec engg; opportunity, exper first consideration. NY or New England. E-525.

M.S.E.E., 30, married. Exper includes tech representative radio concern, research com, devpmt automatic controls and col teaching. Desires devpmt work in electronics or controls. Location immaterial. E-526.

S.B.E.E., Com, MIT '39, single, 21. Location, U.S. Desires work with a commercial broadcasting co. E-527.

E.E., 1934 RPI, married, 26. NJ First Class Steam Engr; 3 yrs modern boiler, turbine oprtg exper; 2 yrs on controls, and meter maintenance. Desires work in pwr plant controls. E-528.

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What this company found: A good punch press operator with good equipment can do much to make dies last longer. But there is a definite limit beyond which this combination cannot go—a limit that depends on the punching qualities of the steel.

What they did about it: They put the problem of prolonging die life squarely up to one of our Electrical Sheet Specialists. Armed with all the facts of the case, this man was able to recommend the U·S·S Electrical Steel Sheet grade which would meet all electrical specifications and, at the same time, substantially increase the life of dies. A test run confirmed this, and the shop has since been punching laminations from U·S·S Electrical Steel Sheets. Die life has gone up 50 per cent.

To help you keep manufacturing costs down to an irreducible minimum, Carnegie-Illinois pays special attention to the punching qualities of U·S·S Electrical Steel Sheets. Because quality is held to such close tolerances, once the press is adjusted no further readjustments are required due to variations in the steel.

It will pay you to call the man from Carnegie-Illinois—today.

ELECTRICAL STEEL SHEETS

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Pittsburgh and Chicago

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United States Steel Products Company, New York, *Export Distributors*

UNITED STATES STEEL

WHICH OF THESE 3 RESISTANCE COATINGS Do You Require?

Your equipment is designed for the temperatures and atmospheric conditions expected in service. IRC Wire Wound Resistors are designed exactly the same way and for the same reasons—to assure maximum dependability and economy. For example:

✔ **IRC TYPE B COATING,** rated at 250° C. rise, is the best and most economical for low range, high power applications under all types of atmospheric conditions.

✔ **IRC TYPE A COATING,** rated at 130° C. rise, provides maximum protection for medium and high resistance requirements in domestic applications involving low power.

✔ **IRC TYPE C COATING,** rated at 130° C. rise, is designed for complete dependability on medium and high resistance values under the worst possible conditions such as those encountered on shipboard, in the tropics or in highly humid climates. It will withstand 9 cycles of the famous boiling hot and zero cold salt water immersion test.

IT PAYS TO KNOW!

Don't buy resistors blindly in the hope that you are getting the most protection for your money! It pays to let IRC engineers study your applications. Their suggestions—based on an exceptionally broad experience in the manufacture of standard and special resistance types—may pave the way to increased dependability and economy.

WRITE *for Wire Wound Resistor Catalog IV. Catalogs covering other resistor types also available on request.*

INTERNATIONAL RESISTANCE CO.

427 N. Broad Street, Philadelphia, Penna.

Makers of Resistance Units of More Types, in More Shapes, for More Applications Than Any Other Manufacturer in the World.

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(See INSTRUMENTS, ELECTRICAL)

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General Electric Co., Schenectady, N. Y.

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National Carbon Co., Inc., Cleveland, O.

BUS BAR SUPPORTS
Burndy Engg. Co., Inc., New York
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CABLE ACCESSORIES
General Electric Co., Schenectady, N. Y.
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(See GENERATORS AND MOTORS)

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Leeds & Northrup Co., Philadelphia
Roller-Smith Co., Bethlehem, Pa.
Weston Elec. Instrument Corp., Newark, N.J.

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General Electric Co., Schenectady, N. Y.
Leeds & Northrup Co., Philadelphia
Roller-Smith Co., Bethlehem, Pa.
Weston Elec. Instrument Corp., Newark, N.J.

Integrating
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General Electric Co., Schenectady, N. Y.
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Mineralac Electric Co., Chicago

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Mineralac Electric Co., Chicago
Roebling's Sons Co., John A., Trenton, N. J.

Moulded
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Paper
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Porcelain
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Okonite Company, The, Passaic, N. J.
Roebling's Sons Co., John A., Trenton, N.J.

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Universal Clay Products Co., Sandusky, O.

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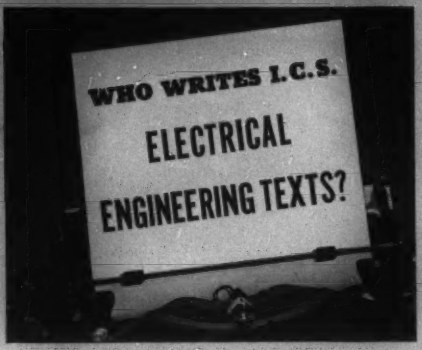

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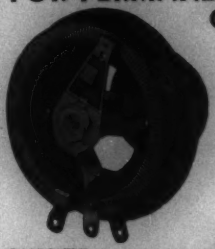

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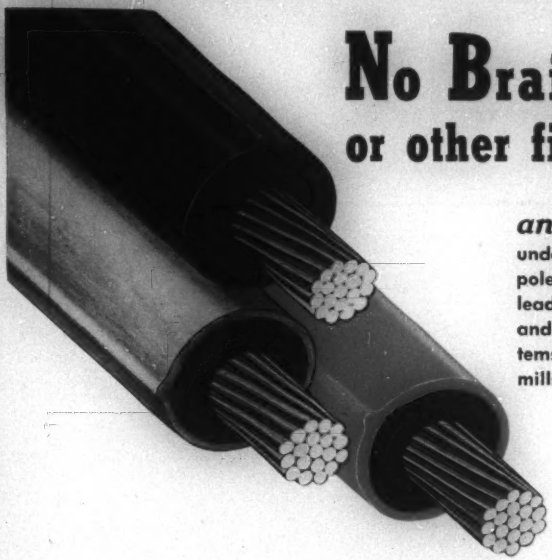

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